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SEISMIC VERIFICATION of Nuclear Testing Treaties

CONGRESS OF THE UNITED STATES   OFFICE OF TECHNOLOGY ASSESSMENT

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Foreword

Since the advent of the atomic bomb there has been interest from both an arms control and environmental perspective to restrict the testing of nuclear weapons. Although the debate over nuclear testing has many facets, verification is a central issue to the consideration of any treaty. At the requests of the Senate Select Committee on Intelligence, the House Committee on Foreign Affairs, and the House Permanent Select Committee on Intelligence, OTA undertook an assessment of seismic capabilities to monitor underground nuclear explosions.

Like an earthquake, the force of an underground nuclear explosion creates seismic waves that travel through the Earth. A satisfactory seismic network to monitor such tests must be able to both detect and identify seismic signals in the presence of "noise," for example, from natural earthquakes. In the case of monitoring a treaty that limits testing below a certain size explosion, the seismic network must also be able to estimate the size with acceptable accuracy. All of this must be done with an assured capability to defeat adequately any credible attempt to evade or spoof the monitoring network.

This report addresses the issues of detection, identification, yield estimation, and evasion to arrive at answers to the two critical questions:

- Down to what size explosion can underground testing be seismically monitored with high confidence?
- How accurately can the yields of underground explosions be measured?

In doing so, we assessed the contribution that could be made if seismic stations were located in the country whose tests are to be monitored, and other cooperative provisions that a treaty might include. A context chapter (chapter 2) has been included to illustrate how the technical answers to these questions contribute to the political debate over:

- Down to what yield can we verify Soviet compliance with a test ban treaty?
- Is the 1976 Threshold Test Ban Treaty verifiable?
- Has the Soviet Union complied with present testing restrictions?

In the course of this assessment, OTA drew on the experience of many organizations and individuals. We appreciate the assistance of the project's contractors who prepared background analysis, the U.S. Government agencies and private companies who contributed valuable information, the project's advisory panel and workshop participants who provided guidance and review, and the many additional reviewers who helped ensure the accuracy and objectivity of this report.

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NOTE: OTA appreciates and is grateful for the valuable assistance and thoughtful critiques provided by the advisory panel members. The panel does not, however, necessarily approve, disapprove, or endorse this report. OTA assumes full responsibility for the report and the accuracy of its contents.

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Chapter 1

Executive Summary

Technologies that were originally developed to study earthquakes may now enable the United States to verify a treaty with the Soviet Union to further limit the testing of nuclear weapons.

INTRODUCTION

Seismology now provides a means to monitor underground nuclear explosions down to low yields, even when strenuous attempts are made to evade the monitoring system. By doing so, seismology plays a central role in verifying arms control agreements that limit the testing of nuclear weapons. Seismology, however, is like any other technology: it has both strengths and limitations. If the capabilities of seismic monitoring are to be fully realized, it is necessary to understand both how the strengths can be used and how the limitations can be avoided.

To a great extent, the capabilities of any given seismic monitoring network are determined by how the monitoring task is approached and what supplementary provisions are negotiated within the treaty. If agreements can be negotiated to reduce uncertainty, then seismology can be very effective and extremely low yields could be monitored with high confidence.

This report addresses two key questions:

1. down to what size explosion can underground testing be seismically monitored with high confidence, and
2. how accurately can the yields of underground explosions be measured seismically?

The answers to these questions provide the technical information that lies at the heart of the political debate over:

1. how low a threshold test ban treaty with the Soviet Union we could verify,
2. whether the 1976 Threshold Test Ban Treaty is verifiable, and
3. whether the Soviet Union has complied with present testing restrictions.

Seismic monitoring as discussed in this study is evaluated without specific references to the particular treaty regime to which it is to apply. There will always be some limit to the capability of any given monitoring network, and hence there will always be a threshold below which a seismic network could not monitor with high confidence. Consequently, should a total test ban be enacted there will be a very low threshold below which seismic methods cannot provide high confidence monitoring. Such a treaty could still be considered to be in the national interest if, taking both seismic and nonseismic verification methods into account, the significance of undetected violations (if they were to occur) would be outweighed by the benefits of such a treaty.

THE TEST BAN DEBATE

Test ban treaties are a seemingly simple approach to nuclear arms control, yet their impact is complex and multi-faceted. The decision as to whether a given test ban treaty is in our overall national interest is dependent on many questions concerning its effects. Disadvantages in one area must be weighed against advantages in another. Consequently, all aspects of a new treaty must be considered together and the cumulative impact evaluated in terms of a balance with the Soviet Union. Finally, the total net assessment of the effects of a

Photo credit: Department of Energy

Signal cables and test device being lowered down test hole.

treaty on our national security must be weighed against the alternative: no treaty.

One's opinion about the effects of a test ban, and thus its desirability, is largely dependent on one's philosophical position about the role of a nuclear deterrent and the extent to which arms control can contribute to national security. It is perhaps because test ban treaties go to the very heart of nuclear weapons policy that the debate over them remains unresolved. Three decades of negotiation between the United

States and the U.S.S.R. have produced only three limitation treaties, two of which remain unratified:

1. **1963 Limited Nuclear Test Ban Treaty (LTBT).** This treaty bans nuclear explosions in the atmosphere, in outer space, and under water. It was signed by the United States and the U.S.S.R. on August 5, 1963 and has been in effect since October 10, 1963. Over 100 other countries have also signed this treaty.
2. **1974 Threshold Test Ban Treaty (TTBT).** This treaty restricts the testing of underground nuclear weapons to yields no greater than 150 kilotons (kt). It was signed by the United States and the U.S.S.R. on July 3, 1974. Although the TTBT has yet to receive the consent of the U.S. Senate, both nations consider themselves obligated to adhere to it.
3. **1976 Peaceful Nuclear Explosions Treaty (PNET).** This treaty is a complement to the TTBT and restricts individual peaceful nuclear explosions (PNEs) to yields no greater than 150 kt, and aggregate yields in a salvo to no greater than 1500 kt. It was signed by the United States and the U.S.S.R. on May 28, 1976. Although PNET has yet to receive the consent of the U.S. Senate, both nations consider themselves obligated to adhere to it.

Nuclear explosions compliant with these treaties can only be conducted by the United and the U.S.S.R. underground, at specific test sites (unless a PNE), and with yields no greater than 150 kt. Although they have had important positive environmental and arms control impacts, these treaties have not prevented the development of new types of warheads and bombs. For this reason, public interest in a complete test ban or a much lower threshold remains strong, and each year a number of proposals continue to be brought before the Congress to limit further the testing of nuclear weapons.

THE MEANING OF VERIFICATION

For the United States, the main national security benefits derived from test limitation treaties are a result of the Soviet Union being similarly restricted. In considering agreements that bear on such vital matters as nuclear weapons development, each country usually assumes as a cautious working hypothesis that the other parties would cheat if they were sufficiently confident that they would not be caught. Verification—the process of confirming compliance and detecting violations if they occur—is therefore central to the value of any such treaty.

"To verify" means to establish truth or accuracy. Yet in the arena of arms control, the process of verification is political as well as technical. It is political because the degree of verification needed is based upon one's perception of the benefits of a treaty compared with one's perception of its disadvantages and the likelihood of violations. No treaty can be considered to be either verifiable or unverifiable without such a value judgment. Moreover, this judgment is complex because it requires not only an understanding of the capabilities of the monitoring systems, but also an assessment as to what is an acceptable level of risk, and a decision as to what should constitute significant noncompliance. Consequently, people with differing perspectives on the role of nuclear weapons in national security and on the motivations of Soviet leadership will differ on the level of verification required.[1]

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[1] This issue is discussed further in chapter 2, *Seismic Verification in the Context of National Security.*

ASPECTS OF MONITORING UNDERGROUND NUCLEAR EXPLOSIONS

Like earthquakes, the force of an underground nuclear explosion creates seismic waves that travel through the Earth. A seismic monitoring network must be able both to *detect* and to *identify* seismic signals. *Detection* consists of recognizing that a seismic event has occurred and locating the source of the seismic signals. *Identification* involves determining whether the source was a nuclear explosion. In the case of a threshold treaty, the monitoring network must also be able to *estimate the yield* of the explosion from the seismic signal to determine if it is within the limit of the treaty. All of this must be done with a capability that can be demonstrated to adequately defeat any credible attempt to *evade* the monitoring network.

If the seismic signals from explosions are not deliberately obscured or reduced by special efforts, seismic networks would be capable of *detecting* and *identifying* with confidence nuclear explosions with yields below 1 kt. What stops this capability from being directly translated into a monitoring threshold is the requirement that the monitoring network be able to accomplish detection and identification with high confidence in spite of any credible evasion scenario for concealing or reducing the seismic signal from a test explosion.

Demonstrating that the monitoring capability meets this requirement becomes complex at lower yields. As the size of the explosion becomes smaller:

- there are more opportunities for evading the monitoring network,
- there are more earthquakes and industrial explosions from which such small clandestine explosions need to be distinguished, and
- there are more factors that can strongly influence the seismic signal.

The cumulative effect is that the lower the yield, the more difficult the task of monitoring against possible evasion scenarios.

The threat of evasion can be greatly reduced by negotiating within a treaty various cooperative monitoring arrangements and testing restrictions. However, there will eventually be a yield below which the uncertainty of any monitoring regime will increase significantly. **The point at which the uncertainties of the monitoring system no longer permit adequate verification is a political judgment of the point at which the risks of the treaty outweigh the benefits.**

Determining the credibility of various evasion methods requires subjective judgments about levels of motivation and risk as well as more objective technical assessments of the capability of the monitoring system. To separate the technical capabilities from the subjective judgments, we will first describe our capability to detect and identify seismic events and then will show how this capability is limited by various possible evasion methods. All considerations are then combined to address the summary question: *How low can we go?*

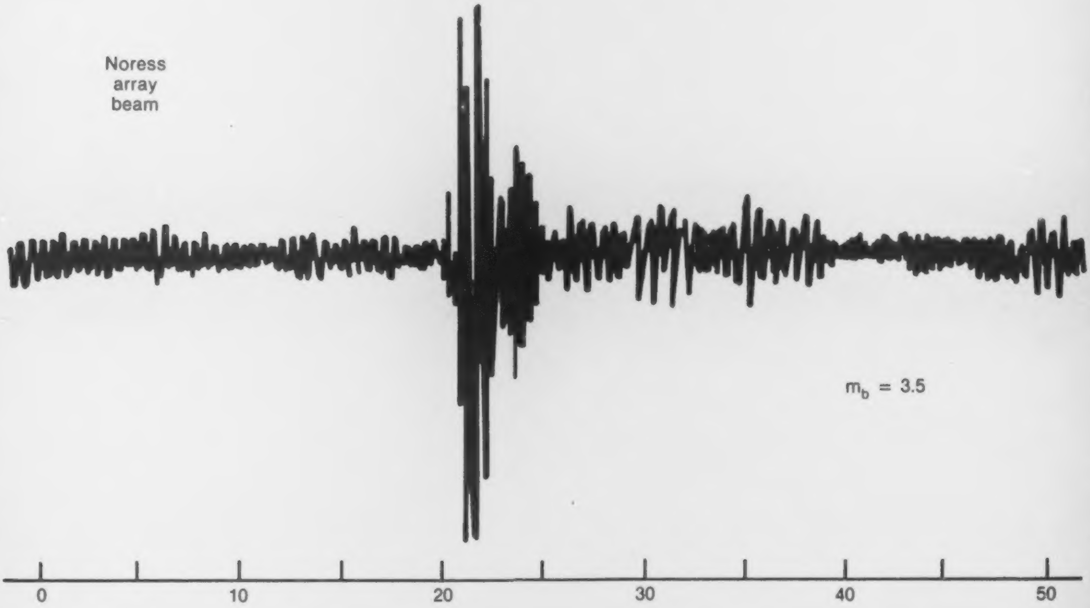
Detecting Seismic Events

The first requirement of a seismic network is that it be capable of detecting a seismic event. If the Earth were perfectly quiet, this would be easy. Modern seismometers are highly sophisticated and can detect remarkably small motions. Limitations are due not to the inherent sensitivity of the instrument but rather to phenomena such as wind, ocean waves, and even rush hour traffic. All of these processes cause ground vibrations that are sensed by seismometers and recorded as small-scale background motion, collectively referred to as "noise." Seismic networks, consisting of groups of instruments, are designed to distinguish events like earthquakes and explosions from this ever-present background noise. The extent to which a seismic network is capable of detecting such events is dependent on many factors. Of particular importance are the types of seismic stations used, the number and distribution of the stations, the amount of background noise at the site locations, and the efficiency with which seismic waves travel from the source to the receiving station through the surrounding geologic area.

Detecting seismic events can be accomplished with high certainty down to extremely small yields. A hypothetical seismic network with stations only *outside* the Soviet Union would be capable of detecting well-coupled[2] explosions with yields below 1 kt anywhere within the Soviet Union and would be able to detect even smaller events in selected regions. The existing seismic array in Norway, for example, has easily detected Soviet explosions with yields of a fraction of a kt conducted 3,800 kilometers away at the Soviet test site in Eastern Kazakhstan (figure 1-1).

Seismic stations within the Soviet Union would further improve the detection capability of a network. In principle, almost any desired signal *detection* level could be achieved within the Soviet Union if a sufficient number of internal stations were deployed. In this sense, the detection of seismic events does not provide a barrier for monitoring even the lowest threshold treaties. From a monitoring stand-

Figure 1-1.—Signal From Semipalatinsk



Seismic signal from a 0.25 kt explosion at the Soviet test site near Semipalatinsk. Recorded 3,800 km away at the NORESS seismic array in Norway on July 11, 1985. The signal to noise ratio is about 30 indicating that much smaller explosions could be detected even at this great distance.

SOURCE: R.W. Alewire III, "Seismic Sensing of Soviet Tests," *Defense 85*, December 1985, pp. 11-21.

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[2] A "well-coupled" explosion is one where the energy is well transmitted from the explosion to the surrounding rock.

point, stations within the Soviet Union are more important for improving *identification* capabilities than for further reduction of the already low detection threshold.

Identifying Seismic Events as Nuclear Explosions

Once a seismic signal has been detected, the next task is to determine whether it was created by a nuclear explosion. Seismic signals are generated not only by nuclear explosions, but also by natural earthquakes, rockbursts in mines, and chemical explosions conducted for mining, quarry blasting, and construction.

Every day there are many earthquakes around the globe whose seismic signals are the same size as those of potential underground nuclear explosions. Several methods can be applied to differentiate earthquakes from underground nuclear explosions. Note, however, that no one method is completely reliable. It is the set of different identification methods taken as a whole and applied in a systematic fashion that is assessed when summaries on capability are given. In this sense, identification is a "winnowing" process.

The most basic method of identification is to use the location and the depth of the event. Over 90 percent of all seismic events in the U.S.S.R. can be classified as earthquakes simply because they are either too deep or not in a plausible location for a nuclear explosion. For seismic events that are in a location and at a

Photo credit: Department of Energy

Craters formed by cavity collapse in Yucca Flat, Nevada Test Site.

depth that could be an explosion, other methods of discrimination based on physical differences between earthquakes and explosions are used.

When a nuclear device explodes underground, it applies uniform pressure to the walls of the cavity it creates. As a result, explosions are seen seismically as highly concentrated sources of *compressional waves,* sent out with approximately the same strength in all directions from the point of the detonated device. An earthquake, on the other hand, occurs when two blocks of the Earth's crust slip past each other along a fault. An earthquake generates *shear waves* from all parts of the fault that rupture.

These fundamental differences between earthquakes and explosions are often exhibited in their seismic signals. As a result, seismologists have been able to develop a series of methods to differentiate the two sources based on the different types of seismic waves they create. The combination of all methods, when applied in a comprehensive approach, can differentiate with high confidence between explosions, down to low yields, and earthquakes.

As the size of the seismic events gets smaller, nuclear explosions must be distinguished not only from earthquakes, but also from other kinds of explosions. Industrial chemical explosions (e.g. in a quarry operation) pose a particularly difficult problem because their seismic signals have physical characteristics similar to those of nuclear explosions. Consequently, the seismic methods that are routinely used to differentiate earthquakes from explosions cannot distinguish between some legitimate chemical explosions for mining purposes and a clandestine nuclear test explosion. Fortunately, industrial explosions in the range of 1 to 10 kt are rare (less than one a year). Large explosions are usually ripple fired so as to minimize ground vibration and fracture rock more efficiently. Ripple firing is often accomplished with bursts spaced about 0.2 seconds apart over a duration of about a second. Recent work suggests that this ripple-firing has an identifiable signature apparent in the observed seismic signals, and therefore can be used to identify such chemical explosions. However, the absence of evidence for ripple firing cannot be taken as evidence that the event is not a chemical explosion. Because of the size consideration, industrial explosions are not an identification problem for normal nuclear explosions above 1 kt. The difficulty, as we will see later, comes in distinguishing between a small *decoupled* nuclear test and a large salvo-fired chemical explosion. This difficulty can be limited through such treaty provisions as options for inspections and constraints on chemical explosions.[3]

Because a seismic signal must be clearly detected before it can be identified, the threshold for identification will always be greater than the threshold for detection. As described in the previous section, however, the detection threshold is quite low. Correspondingly, even a hypothetical network consisting of stations only *outside* the Soviet Union would be capable of *identifying* seismic events with magnitudes corresponding to about 1 kt *if* no attempts were made to evade the monitoring system.[4] Seismic stations within the Soviet Union would further improve the identification capability of a network.

It has been argued that the use of high frequency seismic data will greatly improve our capability to detect and identify low-yield nuclear explosions.[5] [6] Recent experiments conducted by the Natural Resources Defense Council together with the Soviet Academy of Sciences are beginning to provide high frequency seismic data from within the Soviet Union that shows clear recordings of small explosions (see box 1-A). There remains, however, a lack of consensus on the extent to which the use of higher frequency data will actually im-

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[3] See chapter 6, *Evading a Monitoring Network*, for a discussion of treaty constraints.

[4] See chapter 5, *Identifying Seismic Events.*

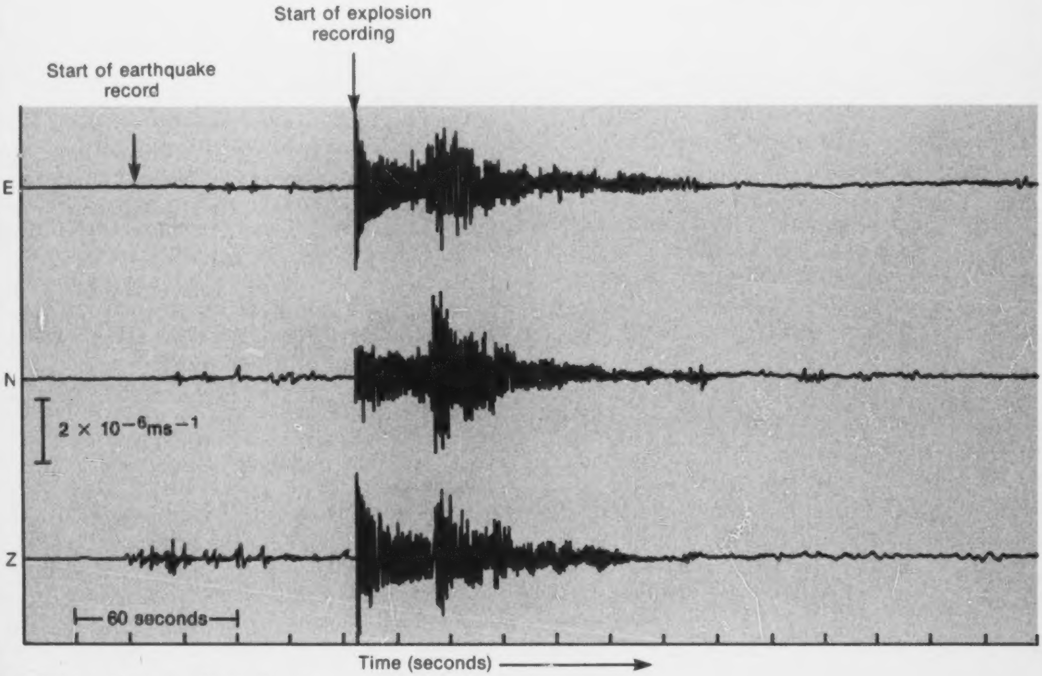
[5] For example, much lower identification thresholds have been defended by J.F. Evernden, C.B. Archambeau, and E. Cranswick, "An Evaluation of Seismic Decoupling and Underground Nuclear Test Monitoring Using High-Frequency Seismic Data," *Reviews of Geophysics*, vol. 24, May 1986, pp. 143-215.

[6] See chapter 4, *Detecting Seismic Events*, and chapter 5 *Identifying Seismic Events*, for discussions of high frequency monitoring.

Box 1-A.—NRDC/Soviet Academy of Sciences

New seismic data from the Soviet Union is becoming available through an agreement between the Natural Resources Defense Council and the Soviet Academy of Sciences. The agreement provides for the establishment of a few high-quality seismic stations within the Soviet Union around the area of the Soviet test site in Kazakhstan. The agreement also included experiments in which the Soviet Union detonated chemical explosions of known yield near the test site so that the test site could be calibrated.

The seismograph below is from a 0.01 kt chemical explosion detonated near the Soviet test site and recorded 255 km away. The signal of the explosion can be clearly seen along with the coincidental arrival of seismic waves caused by a large earthquake that occurred south of New Zealand. The three components of ground motion are east-west (E), north-south (N), and vertical (Z).



SOURCE: Natural Resources Defense Council.

prove monitoring capabilities. The lack of consensus is due to differences in opinion as to how well U.S. experience and the limited experience near the Soviet test site can be extrapolated to an actual comprehensive monitoring system throughout the Soviet Union. Consequently, the debate over improved capability will probably remain unresolved until more extensive data can be collected at regional distances from areas throughout the Soviet Union. Nevertheless, there is general agreement among seismologists that good data is obtainable at higher frequencies than those used routinely today, and that this data offers advantages for nuclear monitoring that should continue to be explored.

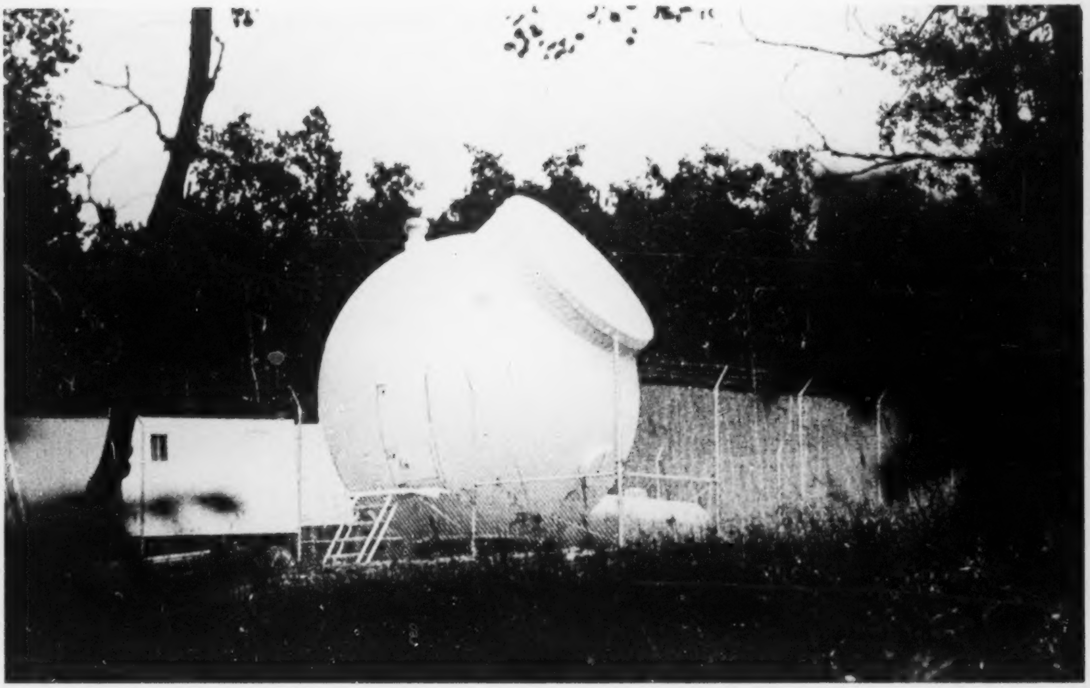


Photo credit: Sandia National Laboratories

An example of what an internal seismic station might look like.

Evading a Seismic Monitoring Network

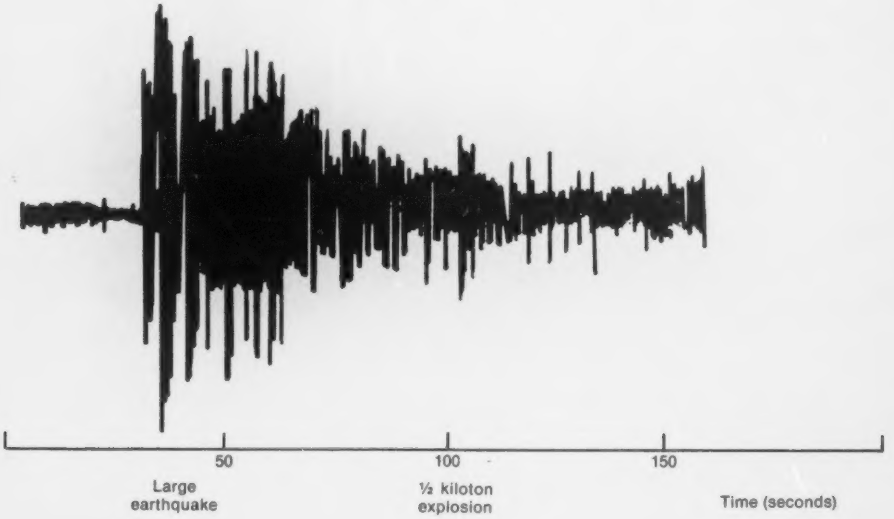
To monitor a treaty, nuclear tests must be detected and identified with high confidence even if attempts are made to evade the monitoring system. As mentioned earlier, it is the feasibility of various evasion scenarios that sets the lower limit on the monitoring capability. The major evasion concerns are:

- that the signal of an explosion could be hidden in the signal of a naturally occurring earthquake,
- that an explosion could be muffled by detonating it in a large underground cavity, or
- that a nuclear test could be disguised as or masked by a large legitimate industrial explosion.

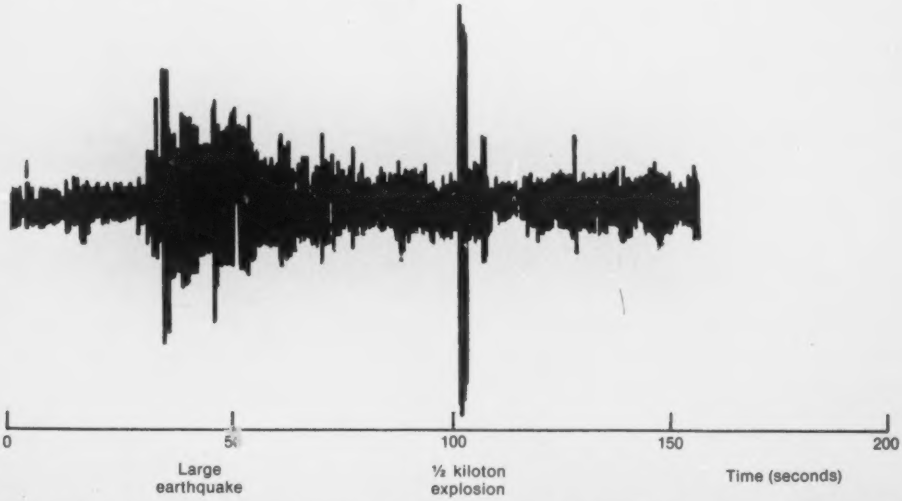
The hide-in-earthquake scenario assumes that a small nuclear test could be conducted by detonating the explosion during or soon after an earthquake. If the earthquake were sufficiently large and the small explosion properly timed, the seismic signal of the explosion would be hidden in the seismic signal of the earthquake. However, it is not practical for an evader to wait for an earthquake that is in the immediate vicinity of the test site. Therefore, the masking earthquake would have to be large and at some distance. The smaller nuclear explosion will produce higher frequency signals than the earthquake, and filtering the signals will reveal the signals from the explosion (figure 1-2). For this and other reasons (chapter 6), the hide-in-earthquake scenario need no longer be viewed as a credible evasion threat for explosions above 5-10 kt. To counter this threat for explosions below 5-10 kt may require access to data from seismic stations within the Soviet Union, because the higher frequency seismic signals from explosions below 5-10 kt

Figure 1-2.—Explosion and Earthquake

Conventional Recording Using Low Frequencies



Same Recording But With High Frequency Passband



Both the upper and lower seismograms were recorded in Norway and cover the same period of time. The upper seismogram is the conventional recording of low-frequency seismic waves. Both it and the lower recording show, at the time of 30 seconds, the arrival of waves from a large earthquake that occurred in the eastern part of the Soviet Union. About one minute after the earthquake, at a time of 100 seconds, the Soviet Union conducted a very small (about ½ kt) underground nuclear explosion at their Kazakhstan test site. With the standard filter (upper seismogram), the signal of the explosion appears hidden by the earthquake. Using a passband filter for higher frequency seismic waves (lower seismogram), the explosion is revealed.

SOURCE: Semiannual Technical Summary for Norwegian Seismic Array for 1984, Royal Norwegian Council for Scientific and Industrial Research, Scientific Report No. 1-84/85.

may not always be picked up by stations outside the Soviet Union.

Decoupling appears to be potentially the most effective of all evasion methods. It involves detonating a nuclear device in a large underground cavity so as to muffle the seismic signal. If the explosion occurs in a large cavity, the explosive stresses are reduced because they are spread over the large area of the cavity wall. At a certain cavity size, the stresses will not exceed the elastic limit of the rock. At such a point, the explosion is said to be "fully decoupled" and the seismic signal becomes greatly reduced. At low seismic frequencies, a fully decoupled explosion may have a signal 70 times smaller than that of a fully coupled explosion. At high frequencies the decoupling factor is probably reduced to somewhere between 10 and 7.

Above 10 kt, decoupling is not considered to be a credible evasion scenario because: 1) the clandestine construction of a cavity large and strong enough to decouple a 10 kt explosion is not feasible; and 2) even if such an explosion were somehow fully decoupled, the seismic signal would stand a good chance of being detected and possibly identified. Therefore, decoupling could be most effective for small explosions up to a few kt, particularly when done in conjunction with a legitimate industrial explosion. For example, a potential evasion method would be to secretly decouple a small nuclear explosion in a large underground cavity and mask or attribute the muffled signals to a large chemical explosion that is simultaneously detonated under the guise of legitimate industrial activity.

As discussed in the section on identification, differentiating a small nuclear explosion from a legitimate industrial explosion associated with mining and quarry blasting is difficult because both produce similar seismic signals. This is not a problem for identification under normal circumstances because industrial explosions in the 1-10 kt range occur less than once a year. However, industrial explosions may create a problem when considering the decoupling evasion scenario. That is, some low-yield decoupled explosions might produce seismic signals comparable to those observed from large chemical explosions and no routine capability has yet been developed to differentiate, with high confidence, between such signals.

None of the evasion scenarios poses any serious problem for monitoring explosions above 10 kt. However, to provide adequate monitoring capability below 10 kt, efforts must be made to limit decoupling opportunities. This would include an internal seismic network and provisions within the treaty (such as pre-notification with the option for on-site inspection) to handle the large numbers of chemical explosions. At a few kt, decoupling becomes possible when considered as part of an evasion scenario. Arranging such a test, however, would be both difficult and expensive; and it is not clear that the evader could have confidence that such a test (even if it were successful) would go undiscovered. However, the possibility remains that a few tests of small magnitude could be conducted and remain unidentified as nuclear explosions.

HOW LOW CAN WE GO?

Given all the strengths and limitations of seismic methods in detecting and identifying Soviet nuclear explosions, combined with the credibility of the various evasion scenarios, the ultimate question of interest for monitoring any low-yield threshold test ban treaty is essentially: *How low can we go?* The answer to that question depends largely on what is negotiated in the treaty. As we have seen, the challenge for a monitoring network is to demonstrate a capability to distinguish credible evasion attempts from the background of frequent earthquakes and legitimate industrial explosions that occur at low yields.

The monitoring burden placed on the seismic network by various evasion scenarios can be greatly lessened if seismology gets some help. The sources of help are varied and numerous: they include not only seismic monitoring but also other methods such as satellite surveillance, radioactive air sampling, communication intercepts, reports from intelligence agents, information leaks, interviews with defectors and emigrés, on-site inspections, etc. **The structure of any treaty or agreement should be approached through a combination of seismic methods, treaty constraints, and inspections that will reduce the uncertainties and difficulties of applying seismic monitoring methods to every conceivable test situation.** Yet with these considerations in mind, some generalizations can still be made about monitoring at various levels.

Level 1—Above 10 kt

Nuclear tests with explosive yields above 10 kt can be readily monitored with high confidence.[7] This can be done with external seismic networks and other national technical means. The seismic signals produced by explosions of this size are discernible and no method of evading a seismic monitoring network is credible. However, for accurate monitoring of a 10 kt threshold treaty it would be desirable to have stations within the Soviet Union for improved yield estimation, plus treaty restrictions for handling the identification of large chemical explosions in areas where decoupling could take place.

Level 2—Below 10 kt but Above 1-2 kt

Below 10 kt and above 1-2 kt, the monitoring network must demonstrate a capability to defeat evasion scenarios. Constructing an underground cavity of sufficient size to fully decouple an explosion in this range is believed to be feasible in salt, with dedicated effort and resources. Consequently, the signals from explosions below 10 kt could perhaps be muffled. The seismic signals from these small muffled explosions would need not only to be detected, but also distinguished from legitimate chemical industrial explosions and small earthquakes. Demonstrating a capability to defeat credible evasion attempts would require seismic stations throughout the Soviet Union (especially in areas of salt deposits), negotiated provisions within the treaty to handle chemical explosions, and stringent testing restrictions to limit decoupling opportunities. If such restrictions could be negotiated, most experts believe that a high-quality, well run network of internal stations could monitor a threshold of around 5 kt. Expert opinion about the lowest yields that could reliably be monitored ranges from 1 kt to 10 kt; these differences of opinion stem from differing judgments about what technical provisions can be negotiated into the treaty, how much the use of high frequencies will improve our capability, and what levels of monitoring capability are necessary to give us confidence that the Soviet Union would not risk testing above the threshold.

Level 3—Below 1-2 kt

For treaty thresholds below 1 or 2 kt, the burden on the monitoring country would be much greater. It would become possible to decouple illegal explosions not only in salt domes but also in media such as granite, alluvium, and layered salt deposits. Although it may prove possible to detect such explosions with an extensive internal network, there is no convincing evidence that such events could be confidently identified with current technology. That is, additional work in identification capability will be required before it can be determined whether such small decoupled explosions could be reliably differentiated from the background of many small earthquakes and routine chemical explosions of comparable magnitude.

Level 4—Comprehensive Test Ban

There will always be some threshold below which seismic monitoring cannot be accomplished with high certainty. A comprehensive test ban treaty could, however, still be considered adequately verifiable if it were determined that the advantages of such a treaty would outweigh the significance of any undetected clandestine testing (should it occur) below the monitoring threshold.

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[7] The United States and the Soviet Union presently restrict their testing to explosions with yields no greater than 150 kt. The bomb dropped on Hiroshima was estimated to have a yield of 13 kt.

ESTIMATING THE YIELD OF NUCLEAR EXPLOSIONS

For treaties that limit the testing of nuclear weapons below a specific threshold, the monitoring network not only must detect and identify a seismic event such as a nuclear explosion but also must measure the yield to determine whether it is below the threshold permitted by the treaty. This is presently of great interest with regard to our ability to verify compliance with the 150-kt limit of the 1974 Threshold Test Ban Treaty.

The yield of a nuclear explosion may be estimated from the seismic signal it produces. Yield estimation is accomplished by measuring from the seismogram the size of an identified seismic wave. When corrected for distance and local effects at the recording station, this measurement is referred to as the seismic magnitude. The relationship between seismic magnitude and explosive yield has been determined using explosions of known yields. This relationship is applied to estimate the size of unknown explosions. The problem is that the relationship was originally determined from U.S. and French testing and calibrated for the Nevada test site. As a result, Soviet tests are measured as if they had been conducted at the Nevada test site unless a correction is made. No correction would be needed if the U.S. and Soviet test sites were geologically identical, but they are not.

The Nevada test site, in the western United States, is in a geologically young and active area that is being deformed by the motion between the North American and Pacific tectonic plates. This recent geologic activity has created an area of anomalously hot and possibly even partially molten rock beneath the Nevada test site. As a result, when an explosion occurs at the Nevada test site, the rock deep beneath Nevada absorbs a large proportion of the seismic energy. The Soviet test site, on the other hand, is more similar to the geology found in the eastern United States. It is a geologically old and stable area, away from any recent plate tectonic activity. When an explosion occurs at the Soviet test site, the cold, solid rock transmits the seismic energy strongly. As a consequence, waves traveling from the main Soviet test site in Eastern Kazakhastan appear much larger than waves traveling from the Nevada test site. Unless that difference is taken into account, the size of Soviet explosions will be greatly overestimated.

The geological difference between the test sites can result in *systematic error*, or "*bias*," in the way that measurements of seismic waves are converted to yield estimates. *Random error* is also introduced into the estimates by the measurement process. Thus, as with any measurement, there is an overall uncertainty associated with determining the size of an underground nuclear explosion. This is true whether the measurement is being made using seismology, hydrodynamic methods, or radiochemical methods. It is a characteristic of the measurement. To represent the uncertainty, measurements are presented by giving the most likely number (the mean value of all measurements) and a range that represents both the random scatter of the measurement and an estimate of the systematic uncertainty in the interpretation of the measurements. It is most likely that the actual value is near the central number and it is increasingly unlikely that the actual number would be found towards either end of the scatter range. When appropriate, the uncertainty range can be expressed by using what is called a "factor of uncertainty." For example, a factor of 2 uncertainty means that the best estimate of the yield (the "measured central value") when multiplied or divided by 2, defines a range within which the true yield will fall in 95 out of 100 cases. This is the high degree of certainty conventionally used in seismology and may or may not be appropriate in a verification context.[8]

The uncertainty associated with estimates of the systematic error can be greatly reduced by negotiating provisions that restrict testing to specific test sites and by calibrating the test sites. If such calibration were to be an integral part of any future treaty, the concern over systematic errors of this kind would become minimal. The majority of errors that would remain would be random. As discussed in chapter 2, a country considering cheating could not take advantage of the random error, because it would not be possible to predict how the random error would act on any given evasion attempt. In other words, if a country attempted to test above the threshold, it would have to realize that with every test the chances of appearing in compliance would decrease and at the same time the chance that at least one of the tests would appear in unambiguous violation would increase. For this reason, the range of uncertainty should not be considered as a range within which cheating could occur.

Most of the systematic error associated with estimating the yields of Soviet nuclear explosions is due to geological differences between the U.S. and Soviet test sites and in the coupling of the explosion to the Earth. Therefore, the single most important thing that can be done to reduce the uncertainty in yield estimation is to calibrate the test sites. Calibration could be accomplished through an exchange of devices of known yield, or through independent measures of the explosive yield such as can be provided by radiochemical or hydrodynamic methods (See box 1-B).

Our present capability to estimate seismically the yields of Soviet explosions is often cited as a factor of two.[9] While this may reflect present operational methods, it is not an accurate representation of our capability. Our capability could be greatly improved by incorporating new methods of yield estimation. Most seismologists feel that if new methods were applied, the resulting uncertainty for measuring explosive yields in the range of 150 kt at the Soviet test site would be closer to a factor of 1.5 than a factor of two.[10] Present methods are stated to be accurate only to a factor of two in part because they have not yet incorporated the newer methods of yield estimation that use surface waves and Lg waves.[11] The uncertainty of this comprehensive approach could be further reduced if calibration shots were performed and testing were restricted to areas of known geologic composition. **It is estimated that through such measures, the uncertainty in seismically measuring Soviet tests could be reduced to a level comparable to the uncertainty in seismically measuring U.S. tests. An uncertainty factor of 1.3 is the current capability that seismic methods are able to achieve for estimating yields at the Nevada test site.**

As with detection and identification, yield estimation becomes more difficult at low yields. Below about 50 kt, high-quality Lg-wave signals can only be reliably picked up by stations within the Soviet Union less than 2,000 km from the test site. For explosions below 10 kt, the uncertainty increases because small explosions do not always transmit their signals efficiently to the surrounding rock. For small explosions, the uncertainty could be reduced by restricting such tests to depths below the water

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[8] See chapter 2, *Seismic Verification in the Context of National Security*.

[9] U. S. Department of State, "Verifying Nuclear Testing Limitations: Possible U.S.-Soviet Cooperation, Special Report No. 152," Aug. 14, 1986.

[10] This reduction of uncertainly derives from using more than one statistically independent method. Consider as an example the situation where there are three independent methods of calculating the yield of an explosion, all of which (for the sake of this example) have a factor of two uncertainty in a log normal distribution:

# of Methods	Resulting Uncertainty
1	2.0
2	1.6
3	1.5

By combining methods, the uncertainty can be reduced below the uncertainty of the individual methods. This methodology, however, can only reduce random error. Systematic error, such as differences between the test site, will remain and limit the extent to which the uncertainty can be reduced unless calibration is performed.

[11] See chapter 7, *Estimating the Yields of Nuclear Explosions*.

table, so that their signal will be transmitted effectively.

Our capability to estimate explosive yields would depend to a large degree on the approach that was taken and what was negotiated in future treaties. If new methods of yield determination were incorporated into the measurements and calibration shots were performed, the capability of seismic methods could be improved to a point comparable to the accuracy of other methods, such as CORRTEX, that require a foreign presence and equipment at the test site. In any case, if the objective of reducing the uncertainty is to reduce the opportunities for cheating, small differences in random uncertainty do not matter.

SOVIET COMPLIANCE

The decision as to what constitutes adequate verification should represent a fair assessment of the perceived dangers of non-compliance. This necessarily involves a weighing of the advantages of the treaty against the feasibility, likelihood, and significance of noncompliance. Such decisions are subjective and in the past have been influenced by the desirability of the treaty and the political attractiveness of particular monitoring systems.[12] Specific concern over compliance with test ban treaties has been heightened by findings by the Reagan Administration that:

> "Soviet nuclear testing activities for a number of tests constitute a likely violation of legal obligations under the Threshold Test Ban Treaty."[13]

Although the 1974 Threshold Test Ban Treaty and the 1976 Peaceful Nuclear Explosions Treaty have remained unratified for over 10 years, both nations have expressed their intent to abide by the yield limit. Because neither the United States nor the Soviet Union has indicated an intention *not* to ratify the treaties, both parties are obligated under international law (Article 18, the 1969 Vienna Convention on the Law of Treaties) to refrain from acts that would defeat their objective and purpose.

In examining compliance with the 150-kt threshold, seismic evidence is currently considered the most reliable basis for estimating the yields of Soviet underground nuclear explosions.[14] The distribution of Soviet tests indicates that about 10 (out of over 200) Soviet explosions since the signing of the Threshold Test Ban Treaty in 1974 *could* have estimated yields with central values above the 150 kt threshold limit, depending on how the estimate is made.[15] These 10 tests could actually be at or below the 150 kt limit, but have higher yield estimates due to random fluctuations in the seismic signals. In fact, when the same methods of yield estimation are applied to U.S. tests, approximately the same number of U.S. tests also appear to be above the 150 kt threshold limit. These apparent violations, however, do not mean that one, or the other, or both countries have cheated; nor does it mean per se that seismology is an inadequate method of yield estimation. It is inherent in any method of measurement that if several tests are performed at the limit, some of these tests will have estimated central values above the yield limit. Because of the nature of measurements (using any method), it is expected that about half the Soviet tests at 150 kt would be measured as slightly above 150 kt and the other half would be measured as slightly below 150 kt.

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[12] See chapter 2, *Seismic Verification in the Context of National Security*.

[13] "The President's Unclassified Report on Soviet Noncompliance with Arms Control Agreements," transmitted to the Congress, Mar. 10, 1987.

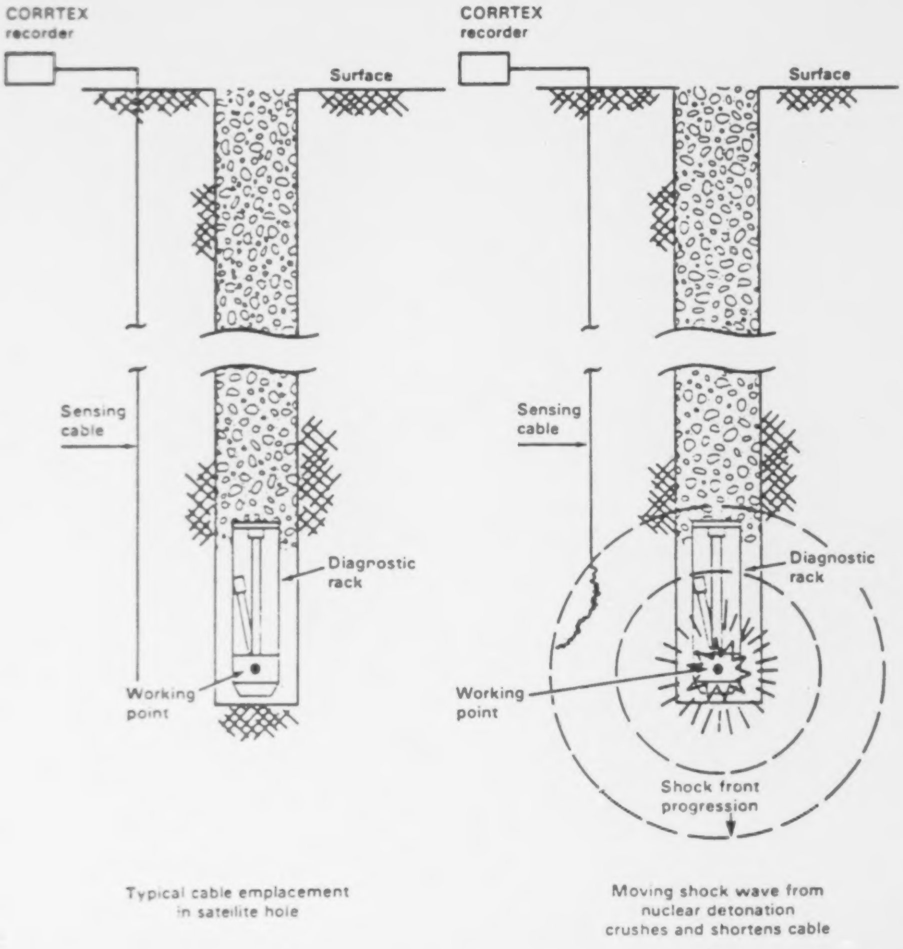
[14] Conclusion of the Defense Intelligence Agency Review Panel as stated in a letter from Roger E. Batzel, Director of Lawrence Livermore National Laboratory to Senator Claiborne Pell on Feb. 23, 1987.

[15] See chapter 7, *Estimating the Yields of Nuclear Explosions.*

Box 1-B.—CORRTEX

CORRTEX (Continuous Reflectometry for Radius versus Time Experiments) is a technique that was developed in the mid-1970s to improve yield estimation using non-seismic (hydrodynamic) methods. In the CORRTEX technique, a satellite hole is drilled parallel to the emplacement hole of the nuclear device and an electrical sensing cable is lowered down the hole (see figure). When the explosion occurs, a shock wave moves outward crushing and electrically shorting the cable.

By measuring with electronic equipment at the surface the rate at which the cable is shorted out, the rate of expansion of the shock wave can be calculated. From the rate of expansion of the shock wave and the properties of the surrounding medium, the yield of the nuclear device can be estimated. A full assessment of this method is presented in the Appendix, *Hydrodynamic Methods of Yield Estimation*.


CORRTEX recorder
Surface
Sensing cable
Diagnostic rack
Working point
CORRTEX recorder
Surface
Sensing cable
Diagnostic rack
Working point
Shock front progression

Typical cable emplacement in satellite hole

Moving shock wave from nuclear detonation crushes and shortens cable

All of the estimates of Soviet and U.S. tests are within the 90 percent confidence level that one would expect if the yields were 150 kt or less. Extensive statistical studies have examined the distribution of estimated yields of explosions at Soviet test sites. **These studies have concluded that the Soviets are observing a yield limit consistent with compliance with the 150 kt limit of the Threshold Test Ban Treaty.**[16] [17]

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[16] Ibid.

[17] One of the first groups to carry out such statistical studies was Lawrence Livermore National Laboratory. Their conclusion was reported in open testimony before the Senate Armed Services Committee on Feb. 26, 1987 by Dr. Milo Nordyke, Leader of the Treaty Verification Program.

VERIFICATION OF THE TTBT AND THE PNET

As noted above, the 1974 Threshold Test Ban Treaty and the 1976 Peaceful Nuclear Explosions Treaty have not been ratified. Most recently, the Senate failed to consent to ratification at least in part because of concerns that the size of Soviet explosions cannot be measured with adequate confidence.[18] As a result, for over 10 years the United States has continued to abide by the treaties, yet refused to ratify them, ostensibly because they cannot be adequately verified. Note that if the treaties were ratified, the protocols would come into force calling for an exchange of data which, if validated, would then improve the verification.[19] [20] However, the treaty contains no provisions for an independent verification of the data, most importantly, the yields of the calibration shots. Therefore, many experts question the value of such data, unless the data can be validated.

As a solution to the problem of uncertainty in yield estimation, the administration has recently proposed the use of an on-site measurement system called CORRTEX for all tests above 50 kt. The CORRTEX system is stated to have a factor of 1.3 uncertainty for measuring yields greater than 50 kt at the Soviet test site.[21] [22] The drawbacks are that it requires prenotification and cooperation of the host country to the extent that foreign personnel and their equipment must be allowed at the test site for each test. Also, CORRTEX has limited application for monitoring a low-yield treaty and none for detecting clandestine testing, and so it would not improve our ability to monitor low-yield testing thresholds.

Alternatively, advanced seismic methods could be used. The advantage of seismic methods is that a continued presence of foreign personnel at the test site would not be necessary. Additionally, our ability to monitor all Soviet testing (not just testing above 50 kt) would be improved. **If the Soviet test site was calibrated and advanced seismic methods were utilized, the uncertainty in seismic yield estimation could be reduced to a level comparable to CORRTEX.** In fact, CORRTEX could be used to confirm independently the yields of the calibration shots. The Soviet Union has already agreed to the use of CORRTEX for one or two such explosions at the Soviet test site.[23]

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[18] *Threshold Test Ban Treaty and Peaceful Nuclear Explosions Treaty*, Hearings before the Senate Committee on Foreign Relations, Jan. 13 and 15, 1987, S. Hrg. 100-115.

[19] The protocol of the TTBT calls for an exchange of geological data plus two calibration shots from each geophysically distinct testing area.

[20] Monitoring would also be improved by the data that would be obtained from all PNE shots that have occurred in the Soviet Union since 1976.

[21] U. S. Department of State, Bureau of Public Affairs, "U.S. Policy Regarding Limitations on Nuclear Testing, Special Report No. 150," August 1986.

[22] See appendix, *Hydrodynamic Methods of Yield Estimation*.

[23] Statement of the Secretary of State of the United States and Minister of Foreign Affairs of the Soviet Union, Dec. 9, 1987.

A PHASED APPROACH

If the policy decision were made that treaties further restricting or eliminating the testing of nuclear weapons are in our national interest, then from a verification viewpoint there is much to be said for a phased approach to this goal. Conceptually, it would begin with a limit that can be monitored with high confidence using current methods, but would establish the verification network for the desired lowest level. The threshold would then be lowered as information, experience, and confidence increase.

For example, the United States and the Soviet Union could begin with a treaty that prohibited testing above 10 kt. This is a level that can currently be well monitored seismically.[24] The verification network negotiated within the treaty, however, would be designed with the goal of monitoring down to the 1-2 kt level. This would include a network of advanced seismic stations throughout the Soviet Union to detect off-site testing plus negotiated provisions to reduce evasion possibilities.[25] Principal among these would be to restrict testing to below the water table and to a specified test site where decoupling opportunities would be limited, to require some special handling (such as pre-notification and on-site inspection) for the detonation of large chemical explosions, and to institute measures to confirm a prohibition on decoupling. To reduce the systematic uncertainty in yield estimation, a series of calibration shots would need to be conducted at each test site using either an independent method such as CORRTEX or the exchange of devices of known yield.

After such a network had been in operation for some time, many of the disagreements concerning hypothetical networks would be resolved. It would be known how well seismic waves travel through the geology of the Soviet Union and what noise levels exist in various areas. Through such a process, experience with large-scale monitoring would be gained and there would be more accurate knowledge of what level of monitoring effort is needed. After this information and experience had been obtained, provisions within the treaty could call for the further reduction of the threshold. At that point, it would be better known down to what level monitoring could be accomplished. If it were determined that a lower threshold could be verified, the testing threshold could be set to the new verifiable limit. By the continuation of periodic reviews, the treaty would always be able to use developments in seismology to maximize the restriction of nuclear testing.

This procedure, however, does not take into account any considerations other than seismic verification. It simply presents the maximum restrictions that could be accomplished from a seismic verification standpoint. Considerations other than seismic verification may result in different thresholds being more desirable. Lower thresholds, or even a complete ban on testing, may be chosen if the political advantages are seen to outweigh the risk, and if the significance of minor undetected cheating is seen to be small when all monitoring methods are considered. Higher thresholds may be chosen to permit certain types of testing or to avoid placing a threshold at a boundary where particularly significant tests could occur at yields only slightly above the threshold.

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[24] Some experts believe that decoupling is not feasible above 5 kt and consequently, that a 5 kt threshold could be well monitored with existing methods and facilities; while others would place the threshold somewhere between 5 and 10. However, virtually all experts agree that tests above 10 kt can be well monitored, even assuming the monitored country is intent on cheating.

[25] See chapter 6, *Evading a Monitoring Network*.

Chapter 2

Seismic Verification in the Context of National Security

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Chapter 2

Seismic Verification in the Context of National Security

Seismic monitoring is central to considerations of verification, test ban treaties, and national security.

THE ROLE OF VERIFICATION

For an arms control agreement to be successful, each participating country must feel that the provisions of the treaty will enhance its own national security. This requires an evaluation by each country of the costs and benefits to its national security of the treaty's restrictions. In the case of nuclear test ban treaties, the cost is accepting restrictions on the ability to test nuclear weapons. In return for paying this price, each country gains the direct benefit of similarly restricting the other country. In addition to the direct benefits of the agreement, participating countries can also gain the political and non-proliferation benefits of working for arms control, as well as the environmental benefits of reducing the hazards of radioactive contamination of the environment from testing.

In considering agreements that bear on such vital matters as a restriction on nuclear weapon's development, each country may assume as a cautious working hypothesis that the participants would cheat if they were sufficiently confident that they would not be caught. Verification is a process that is undertaken to confirm treaty compliance and, therefore, the ability of the United States to monitor Soviet activity is central to the value of any such treaty.

Verification is most often viewed as a process that improves confidence in a treaty. The converse, however, is also true. Establishing a treaty generally improves our ability to monitor Soviet activity. In this way, monitoring and treaties have a mutually beneficial relationship. The United States monitors Soviet weapons developments whether or not a treaty exists, because the information is important for our national security. Treaties make monitoring easier and more accurate, because they include provisions explicitly intended to aid verification. Additionally, treaties create paths of communication that can be used to resolve, clarify, or correct ambiguous situations. In this sense, treaties have national security value that extends beyond their direct purpose.

Verification of treaties is a complex process. The question of whether a treaty is "verifiable" cannot be answered in any absolute or technical sense. It can only be answered relatively by referring to values that are influenced by a wide range of political and philosophical viewpoints. Consequently, verification involves not only technical considerations, but also judgements as to how these technical considerations translate into the policy world.

In the past several years, Congress has been asked to consider proposals for treaties that prohibit testing above various thresholds. Each proposal has sparked controversy within both the technical and policy communities. For any given treaty, some within both communities will claim it is "verifiable," whereas others will assert that the Soviet Union would be able to cheat and hence that stricter verification provisions are needed to ensure our national security. This chapter is intended to provide a framework for understanding how to weigh the risks and benefits of such treaties.

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THE DEFINITION AND VALUE JUDGMENT OF "VERIFICATION"

In the case of test ban treaties, measures are taken to ensure that the advantages of the treaty cannot be undermined by the other country testing clandestinely. These measures, assessments of the measures' capabilities, evaluations of the risks and benefits, and the political climate within which all of these judgments are made make up the process referred to as verification.

"To verify" means to establish truth or accuracy. Realistically, in the arena of arms control, verification can never be perfect or absolute: it necessarily involves uncertainty and this is often described in probabilistic terms. Because the process of verification involves determining acceptable levels of uncertainty, it is political as well as scientific. The degree of verification needed is based on one's perception of the benefits of the treaty compared with one's perception of the disadvantages and the likelihood of violations. **Consequently, the level of verification required will always be different for people with different perspectives.**

In U.S.-Soviet agreements, the concern about verification is exacerbated by societal asymmetries whereby monitoring compliance is usually achieved more easily in the United States than in the Soviet Union. These asymmetries may cause the United States to insist on stricter verification procedures than the Soviets would judge are needed. This difference makes negotiations difficult, and can create the impression that the United States is obstructing negotiations.

A country considering cheating would have to evaluate the risks and costs of being caught against the benefits of succeeding. A country concerned about preventing cheating has to guess the other country's values for making this decision and then evaluate them against their own estimations of the advantages of the treaty compared with the risk of violation. If the countries lack insight into each other's value systems and decision processes, this uncertainty will result in the perception that a high degree of verification is needed. As a result, the degree of verification needed to satisfy the concerned country may be higher than what is really needed to discourage cheating.

To illustrate this argument, it is useful to consider the analogy of a treaty restricting each party to one side of a river. If the river freezes over, one or both countries may consider crossing to the other side. If the water is deep and there is nothing worth having on the other side, then the ice does not have to be very thin to discourage a party from crossing. If, on the other hand, the water is shallow and there is something of great value to be obtained from the other side, than the ice must be very thin to discourage a party from crossing. The thinness of the ice combined with the depth of the water is the degree of deterrent available to dissuade a party from trying to cross the ice. How thin it has to be to actually deter depends on each party's perception of the risk and the reward. In arms control, crossing the ice represents cheating on a treaty. The level of verification capability needed to deter crossing (the thinness of the ice) depends on each side's perception of the risks and rewards of cheating. The attraction of cheating (getting to the other side) would be the belief that it could result in some sort of advantage that would lead to a significant improvement to the country's national security. The consequence of being caught (falling through the ice) would depend on the depth of the water. This would involve international humiliation, the possible abrogation of the treaty resulting in the loss of whatever advantages the treaty had provided, and the potential loss of all other present and future agreements.

ARE TEST BAN TREATIES IN OUR NATIONAL INTEREST?

Test Ban treaties are a seemingly simple approach to arms control, yet their impact is complex and multi-faceted. Determining the advantages of such a treaty depends upon weighing such questions as:

- Is testing necessary to develop future weapon systems? Do we want both the United States and the Soviet Union to develop new weapon systems?
- Is testing necessary to ensure a high degree of reliability of the nuclear stockpile? Do we want the nuclear arsenals of both the United States and Soviet Union to be highly reliable?
- Is continued testing necessary to maintain high levels of technical expertise in the weapons laboratories? Do we want to continue high levels of expertise in both the United States and Soviet weapons laboratories, and if so, for what purposes?
- Is testing necessary to ensure the safety of nuclear devices?
- Could more conservative design practices reduce the need for nuclear testing?
- Would the effects of a test ban impact the United States and the Soviet Union differently?
- Would a decrease in confidence in nuclear weapons' performance increase or decrease the likelihood of nuclear war?
- Would a test ban treaty discourage nuclear proliferation? Could it be extended to cover other nations?
- Would the effects of a treaty be stabilizing or destabilizing?
- Overall, do the advantages outweigh the disadvantages?

Due to the immense uncertainties associated with nuclear conflict, there are few definitive answers to these questions. One's opinion about the answers is largely dependent on one's philosophical position about the role of a nuclear deterrent, and the extent to which arms control can contribute to national security. None of these questions, moreover, can be considered in isolation. Disadvantages in one area must be weighed against advantages in another. Consequently, all aspects of a new treaty must be considered together and their cumulative impact evaluated in terms of a balance with the Soviet Union. Such a net assessment is difficult because even greater uncertainty is introduced when we try to guess how a given

Box 2-A.—First Interest in Test Ban Treaties

Interest in restricting the testing of nuclear weapons began with an incident that occurred over 30 years ago. On February 26, 1954, an experimental thermonuclear device, named *Bravo*, was exploded on the Bikini Atoll in the Pacific Ocean. The explosion was the United States' 46th nuclear explosion. It produced a yield equivalent to 15 million tons of TNT, which was over twice what was expected. The radioactive fallout covered an area larger than anticipated and accidently contaminated an unfortunate Japanese fishing boat named *Lucky Dragon*. When the boat docked at Yaizu Harbor in Japan, twenty-three of the crew had radiation sickness resulting from fallout. The captain of the vessel, Aikichi Kuboyana, died of leukemia in September 1954. In another such accident, radioactive rain caused by a Soviet hydrogen bomb test fell on Japan. These incidents focused worldwide attention on the increased level of nuclear testing and the dangers of radioactive fallout. Soon after, the first proposal for a test ban was put forth.* The 1954 proposal presented by India's Prime Minister Jawaharlal Nehru was described as:

> . . . some sort of what may be called "standstill agreement" in respect, at least, of these actual explosions, even if the arrangements about the discontinuance of production and stockpiling must await more substantial agreements among those principally concerned.

Since that time over 1,600 nuclear explosions have occurred and at least four more countries (United Kingdom, France, People's Republic of China, and India) have successfully tested nuclear devices.

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*See Bruce A. Bolt, *Nuclear Explosions and Earthquakes*, W.H. Freeman and Company, 1976.

treaty would affect the Soviet Union. Finally, the total net assessment of the effects of a treaty on our national security must be weighed against the alternative: no treaty.

The first formal round of negotiations on a comprehensive test ban treaty began on October 31, 1958 when the United States, the Soviet Union, and the United Kingdom opened, in Geneva, the Conference on the Discontinuance of Nuclear Weapon Tests. Since then, interest in a test ban treaty has weathered three decades of debate with a level of intensity that has fluctuated with the political climate.[1] During this time, three partial nuclear test limitation treaties were signed. Nuclear explosions compliant with these restrictions are now conducted only underground, at specific test sites, and at yield levels no greater than 150 kilotons (kt). These three treaties are:

1. **1963 Limited Nuclear Test Ban Treaty (LTBT).** *Bans nuclear explosions in the atmosphere, outer space, and under water.* This treaty was signed August 5, 1963. Ratification was advised and consented to by the United States Senate on September 24, 1963 and the treaty has been in effect since October 10, 1963.
2. **Threshold Test Ban Treaty (TTBT).** *Restricts the testing of underground nuclear weapons by the United States and Soviet Union to yields no greater than 150 kt.* This treaty was signed July 3, 1974. It was submitted to the United States Senate for advice and consent to ratification on July 29, 1976 and again on January 13, 1987. It remains unratified, but both nations consider themselves obligated to adhere to it.
3. **Peaceful Nuclear Explosions Treaty (PNE).** *This treaty is a complement to the TTBT. It restricts individual peaceful nuclear explosions by the United States and Soviet Union to yields no greater than 150 kt, and aggregate yields to no greater than 1,500 kt.* This treaty was signed May 28, 1976. It was submitted to the United States Senate for advice and consent to ratification on July 29, 1976 and again on January 13, 1987. It remains unratified, but both nations consider themselves obligated to adhere to it.

Although these treaties have fallen far short of banning nuclear testing, they have had important environmental and arms control impacts. Since 1963, no signatory country compliant with these treaties has tested nuclear weapons in the atmosphere, in outer space, or under water, thus eliminating a major environmental hazard. And from an arms control perspective, testing of warheads over 150 kt has been prohibited since 1974.

While these treaties have had important positive impacts, figure 2-1 illustrates that, in fact, they have not resulted in any decline in the amount of testing. The development of new types of warheads and bombs has not been limited by restricting testing, and so advocates of test ban treaties continue to push for more restrictive agreements.

A Comprehensive Test Ban Treaty was the declared goal of the past six U.S. Administrations, but remained elusive. The Reagan Administration, however, has viewed limitations on nuclear testing as not in the national security interests of the United States, both at present and in the foreseeable future. The stated policy of the Reagan Administration is as follows:

> A Comprehensive Test Ban (CTB) remains a long-term objective of the United States. As long as the United States and our friends and allies must rely upon nuclear weapons to deter aggression, however, some nuclear testing will continue to be required. We believe such a ban must be viewed in the context of a time when we do not need to depend on nuclear deterrence to ensure international security and stability and when we have achieved broad, deep, and verifiable arms reductions, substantially improved verification capabil-

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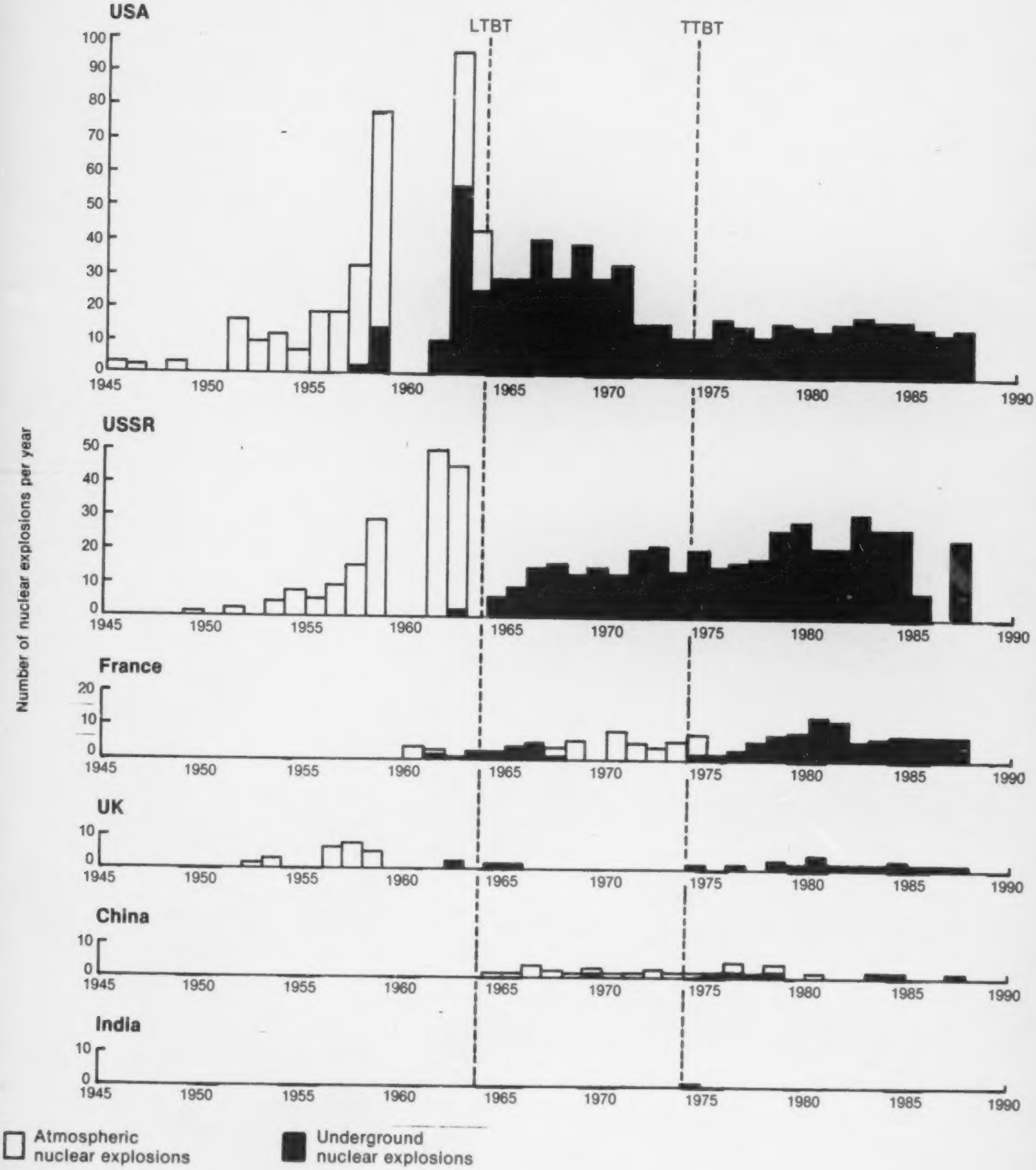
[1] For an overview of the history of test ban negotiations, the reader is referred to G. Allen Greb, "Comprehensive Test Ban Negotiations 1958-1986: An Overview," in *Nuclear Weapon Tests: Prohibition or Limitation?*, edited by Jozef Goldblat and David Cox, SIPRI, CIIPS, Oxford University Press, London, 1987.

Figure 2-1.—Nuclear Testing, July 16, 1945-December 31, 1987



SOURCE: Data from the Swedish Defense Research Institute ities, expanded confidence building measures, and greater balance in conventional forces.[2]

Despite this declared United States position, public interest in a test ban remains strong. Recently, a series of events have heightened worldwide interest in test ban treaties and a number of proposals have been brought before Congress to further limit the testing of nuclear weapons (see box 2-B). To evaluate these proposals requires an understanding of the desired and available levels of verification needed to monitor compliance.

Box 2-B.—Recent Interest in Nuclear Test Limitations

August 6, 1985 to February 26, 1987: The Soviet Union observes a 19-month unilateral test moratorium. Upon ending its moratorium, the Soviet Union declares that testing would be stopped again as soon as a U.S. testing halt was announced.

February 26, 1986: House Joint Resolution 3 (with 207 cosponsors) passes the House with a vote of 268 to 148, requesting President Reagan to resume negotiations with the Soviet Union towards a comprehensive test ban treaty and to submit to the Senate for ratification the Threshold Test Ban Treaty (TTBT) and the Peaceful Nuclear Explosions Treaty (PNE). The wording of the House Resolution is nearly identical to a similar proposal which previously passed the Senate by a vote of 77 to 22 as an amendment to the 1985 Department of Defense (DoD) Authorization Bill.

May 28, 1986: The Natural Resources Defense Council, a private environmental group, signs an agreement with the Soviet Academy of Sciences for the establishment of three independent seismic monitoring stations near the principal nuclear test sites of each country. The agreement specifies that the stations are to be jointly manned by American and Soviet scientists and the data is to be made openly available.

Summer 1986: UN Conference on Disarmament agrees to a global exchange by satellite of sophisticated seismic data.

August 7, 1986: The Five Continent Peace Initiative formed by the leaders of six nonaligned countries (India, Sweden, Argentina, Greece, Mexico, and Tanzania) urges a fully verifiable suspension of nuclear testing and offers assistance in monitoring the ban.

August 8, 1986: House of Representatives votes 234 to 155 in favor of an amendment to the Defense Authorization Bill that would delete funding in calendar year 1987 for all nuclear tests with yields larger than 1 kt, provided that the Soviet Union does not test above 1 kt and that the Soviet Union accepts a U.S. monitoring program. The House Amendment is dropped prior to the Reykjavik summit when the Administration agrees to submit the TTBT and PNET to the Senate for advice and consent.

May 19, 1987: House of Representatives votes 234 to 187 in favor of an amendment to the fiscal year 1988 DoD Authorization Bill to delete funding for all nuclear tests with yields larger than 1 kt during fiscal year 1988 provided that the Soviet Union does the same and, if reciprocal (in-country) monitoring programs are agreed on and implemented.

July 1987: At the expert talks on nuclear testing, Soviets propose calibration of test sites to reduce the uncertainty in yield estimates. The proposal invites U.S. scientists to the Soviet nuclear testing site to measure Soviet test yields using both the CORRTEX system and seismic methods. In return, Soviet scientists would measure a U.S. test at the Nevada test site using both methods.

November 9, 1987: Formal opening of negotiations in Geneva on nuclear test limitations.

January 1988: Teams of U.S. and Soviet scientists visit each other's test site to prepare for joint calibration experiments to reduce uncertainty in yield estimation.

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[2] U.S. Department of State, Bureau of Public Affairs, "U.S. Policy Regarding Limitations on Nuclear Testing," Special Report No. 150, Washington, DC, August 1986.

EVALUATING THE CAPABILITY OF A VERIFICATION NETWORK

Making a decision on whether verification is adequate requires an understanding of the capability of the verification system, the significance of the potential violation, and a decision as to what is an acceptable level of risk. Developing the basis for the decision is difficult because it involves two different communities: those who can assess the system's capabilities (a technical question) generally do not form the same community as those who are officially responsible for assessing the overall risks and benefits (a policy question).

For policymakers to weigh the benefits of the treaty against the risks posed by the possibility of unilateral noncompliance, a clear understanding of the capabilities of the monitoring system is necessary. In the frozen river example, this understanding would result from measurements of how thin the ice is and a technical interpretation of how much weight the ice can bear. The decision as to what constitutes an acceptable level of risk is a policy decision because it is based on an assessment of the overall benefits of the treaty weighed against the risk. In the frozen river example, this assessment would represent the decision as to how thin the ice would need to be to deter crossing, how deep the river is, and how significant a crossing would be.

The burden on the policy-making community, therefore, is to understand technical descriptions of the verification system's capability and incorporate this knowledge into their risk-benefit decision. As we shall see, the difficulty is that monitoring capabilities are not certain, but rather they can only be described in probabilistic terms. For example: What are the chances that a clandestine nuclear test above a certain yield could go undetected? What are the chances that a detected seismic event of a certain magnitude could have been a nuclear explosion rather than an earthquake? If an underground nuclear explosion is recorded, how certain can we be that the yield of the explosion was below a specific threshold? The answers to these questions can be obscured by the manner in which they are portrayed. In particular:

- differences between verification systems can be made to look superficially either large or small,
- opportunities for Soviet cheating can be misrepresented, and
- the decision of what defines adequate verification can be made through an arbitrary process.

The next three sections illustrate the issues that arise in assessing a verification capability —and the misrepresentations that are possible—by considering a question that aroused much Congressional interest in early 1987: **What is our ability to measure seismically the yields of Soviet explosions near the 150 kiloton limit of the Threshold Test Ban Treaty?** The first section presents the statistical representations that are used to describe yield estimation. This includes the meaning of uncertainty and confidence levels, along with a comparative discussion that enables the reader to understand what changes in the uncertainty represent. The next section examines how these uncertainties translate into opportunities for Soviet cheating. And finally, the third section illustrates how the policy decision of what constitutes adequate yield estimation capability has changed in apparent response to variations in the attractiveness of particular monitoring systems.

Uncertainty and Confidence Levels

In determining the verifiability of the 1974 Threshold Test Ban Treaty, policymakers wanted to know the capabilities of a seismic monitoring system for estimating whether Soviet tests are within the treaty's limits. The description of such capabilities is accomplished through the use of statistics. While the statistical calculations are relatively straightforward, difficulties arise in correctly appreciating what the numbers mean. To illustrate how such presentations can be misleading, we will first use an example from a common and comparatively well-understood event:[3]

> At the end of the 1971 baseball season, the San Francisco Giants were playing the Los Angeles Dodgers in a televised game. In the first inning, Willie Mays, approaching the end of his illustrious career, hit a home run. Now, one expects that hitting a home run in the first inning should be a rather unusual occurrence because the pitcher is at his strongest and the batter has not had time to get used to the pitcher. In any case, Willie Mays hit a home run and it triggered what every baseball fan would recognize as a typical baseball statistician's response. The calculations were made and it was discovered that, of the 646 home runs Mays had hit, 122 of them had been hit in the first inning: 19 percent! In the most unlikely one-ninth of the innings, Willie Mays had hit nearly one-fifth of his home runs. This realization captured the interest of the reporting community and was discussed extensively in the media. In response to the publicity, the Giants' publicity director explained it by saying that "... Willie was always surprising pitchers in the first inning by going for the long ball before they were really warmed up." The power of statistical analysis was able to draw out the hidden truths about Willie Mays' performance.

Although the data and calculations were correct, the interpretation could not have been more wrong. Throughout Mays' career, he had almost always batted third in the Giants' lineup (occasionally, he batted fourth). That meant he almost always batted in the first inning. Because he averaged about four at-bats per game, approximately one-quarter of his at-bats came in the first inning. Therefore, he only managed to hit 19 percent of his home runs during the first inning which comprised 25 percent of the time that he was at bat. Of the millions of people who must have heard and read about the item, not one pointed out the misinterpretation of the statistic. This included not just casual observers, but also experienced professionals who spend their careers interpreting just that kind of information.

The point here is that the interpretation of numbers is tricky and statistical presentations can often be misleading. The real challenge is not in calculating the numbers, but in correctly interpreting what different numbers mean. In an area with as many technical considerations and political influences as arms control verification, one has to be particularly careful that different numbers represent truly significant differences and not just arbitrary distinctions.

As with every real-world measurement, estimating the size of a nuclear explosion results in variation, or scatter, among the estimates. The use of different instruments at different locations, interpretations of the measurements by different people in slightly different ways, and unknown variations in signals being observed result in slightly different estimates. Similarly, if one were to measure the daily temperature outside using a number of thermometers located in several areas, there would be slight differences in the temperature depending on the particular thermometer, its location (surrounded by buildings and streets, or in a park), how each scale was read, etc.

In seismology, errors come from the instrumentation, from the interpretation of the data, from our incomplete knowledge about how well an explosion transmits its energy into seismic waves (the coupling), and from our limited understanding of how efficiently seismic waves travel along specific paths (the path bias). Some of these errors are random—they vary unpredictably from one measurement to the next. Other errors are not random, but are systematic and are the same from one measurement to the next.

In our example of measuring temperature, a systematic error would be introduced if each reading were made using an improper zero on the thermometer. With such a systematic error, the measurements would continue to be distributed randomly, but the distribution would be shifted by the difference between the true and incorrect zero. The distance from the incorrect value to the actual value would represent the size of the systematic error. In seismology, an example of a systematic error results from the failure to allow correctly for the difference in seismic transmission between the United States and Soviet test sites. The bias term added to the calculation corrects for this effect, although there still remains an uncertainty associated with the bias.

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[3] This example is paraphrased from David L. Goodstein, *States of Matter* (Englewood Cliffs, NJ: Prentice-Hall) 1975.

The distinction between random and systematic errors, however, is not a clear boundary. In many cases, random errors turn out to be systematic errors once the reason for the error is understood. However, if the systematic errors are not understood, or if there are lots of systematic errors all operating in different ways, then the systematic errors are often approximated as random error. In such cases, the random uncertainties are inflated to encompass the uncertainties in estimating the systematic effect. In monitoring the yields of Soviet testing near 150 kt, most of the uncertainty is associated with estimation of systematic error because the test site has not been calibrated. In describing the capability to measure Soviet tests, the estimate of the random error has been inflated to account for the uncertainties in the systematic error.

We will see in the next section that while systematic errors might be exploited if they happen to be to one country's advantage, random errors do not provide opportunities for cheating. Furthermore, the uncertainty in the estimates of the systematic errors can often be significantly reduced by negotiating into the treaty such provisions as the calibration of each test site with explosions of known yield. For this reason, calibration is important and should certainly be part of any future agreement. But, before we discuss how random and systematic errors affect monitoring, the method of statistically describing the capabilities needs to be explained. For this, it is useful to return to our temperature example.

While collecting measurements of the daily temperature by using many thermometers in many locations, we would find that some of the measurements were high and some were low, but most of them were somewhere in the middle. If all of the measurements were plotted, they would cluster around one number with roughly equal scatter distributed to either side. It would be most likely that the best actual value for the daily temperature would be near the central number and it would be increasingly less likely that the actual value would be off towards either end of the scatter distribution.

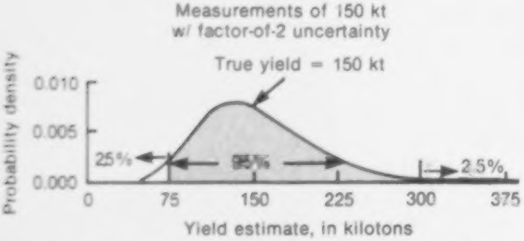
In seismology, that central number, measured using several techniques from many seismometers located in different locations, is referred to as the "central value yield." No matter how accurately we could measure the yields of explosions known to be 150 kt, we would still expect—due to the normal random scatter of measurements and presuming there were no systematic error—that roughly half the explosions would be recorded as being below 150 kt and roughly half would be recorded as being above 150 kt. The width of the distribution above and below depends on the capability of the measuring system and can be described using a "factor of uncertainty."

Unless otherwise stated, the factor of uncertainty for a given measurement is defined as that number which, when multiplied by or divided into an observed yield, bounds the range which has a 95 percent chance of including the actual (but unknown) value of the yield. There is only a 5 percent chance that the measurement would be off by more than this factor. For example, a "factor of 2" uncertainty would mean that the measured central value yield, when multiplied and divided by two, would define a range within which the true yield exists 95 percent of the time.

Naturally, the more confident one wants to be that the true value lies within a given range, the larger that range will have to be. The 95 percent range is used by convention, but there is no real reason why this should be the confidence level of choice for comparing monitoring systems. Using a different confidence level than 95 percent to define the factor of uncertainty would cause the factor to have a different value.

As an example, imagine that all Soviet explosions are detonated with an actual yield of 150 kt and that these explosions are measured

Figure 2-2.—Measurements of 150 kt With Factor-of-2 Uncertainty



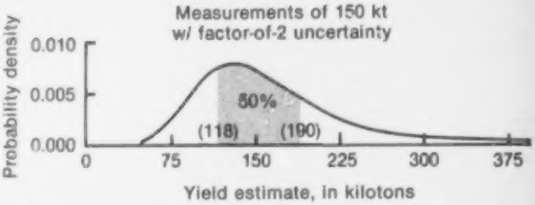
Measurements of a 150 kt explosion using a factor-of-2 uncertainty would be expected to have this distribution. The probability that the actual yield lies in a particular range is given by the area under the curve. Ninety-five percent of the area lies between 75 and 300 kt.

by a monitoring system described as having a factor of 2 uncertainty. It would then follow that 95 percent of the yield estimates will be between 75 and 300 kt. Therefore, if the Soviets conduct 100 tests all at 150 kt, we would expect that about 5 of them would be measured with central yields either above 300 kt or below 75 kt. This is graphically illustrated in figure 2-2, where the probability that the actual yield lies in a particular range is given by the area under the curve over that range.

Although the range from 75 to 300 contains 95 percent of the measurements, we can see that for the distribution assumed (the normal distribution) most of the measurements are, in fact, much closer to the actual yield. For example, figure 2-3 showing the 50 percent confidence level for the same distribution illustrates that over half of the measurements will fall between 118 and 190 kt.

On the other hand, if one wanted to specify a range in which 99 percent of the measurements fall, the range would have to be extended to 60 to 372 kt. In real yield estimation, however, there is no meaningful distinction between 95 percent confidence and 99 percent confidence. The normal distribution is used as a convenience that roughly represents reality near the center of the distribution. The tails of the distribution are almost certainly not close approximations of reality. The general point can still be made: namely that, it takes ever greater increases in range for slight improvements in the confidence level. Table 2-1 illustrates this for the case of a normal distribution by showing how the yield range varies for given factors of uncertainty at various confidence levels.[4]

Figure 2-3.—Fifty-Percent Confidence Level for Measurements of 150 kt With Factor-of-2 Uncertainty



Same distribution as figure 2-2 with 50 percent of the area marked. Over 50 percent of the measurements would be expected to fall within 118 and 190 kt.

From the table, it is clear that a quoted range of values is highly dependent not only on the factor of uncertainty of the monitoring system, but also on the chosen confidence level. For example, the same quoted uncertainty range

Table 2-1.—Confidence Intervals for an Explosion Measured at 150 kt

CONFIDENCE LEVEL	UNCERTAINTY *Factor of 2*	 *Factor of 1.5*	 *Factor of 1.3*
99%	61-372	88-255	106-211
95%	75-300	100-225	115-195
90%	84-269	106-212	120-187
80%	96-236	116-195	126-179
70%	104-216	121-186	130-173
50%	118-191	130-173	138-164

SOURCE: Office of Technology Assessment, 1988.

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[4] Table 2-1 can be read as follows: "If an explosion is measured at 150 kt using a system with a factor of [1.5] uncertainty, the [70 percent] percent confidence ranges from [121 to 186] kt."

that can be achieved using a factor of 1.3 monitoring system at the 95 percent confidence level can be achieved using a factor of 1.5 monitoring system at the 80 percent confidence level, or even using a factor of 2 monitoring system at the 50 percent confidence level.

In selecting an appropriate confidence level to use for quoting uncertainty, the purpose of the comparison must also be recognized. In the case of monitoring compliance with a threshold test ban treaty, one is concerned that intentional cheating could be missed or that unacceptable false alarms could occur. It must be remembered, therefore, that the uncertainty describes the likelihood that the actual value will not fall *either* above or below the range. For example, the 95 percent confidence level means that given repeated trials there is only a 5 percent chance the true yield was *either* above or below the range of the measured yield. In other words, there is a 2.5 percent chance that it could have been above the range and a 2.5 percent chance that it could have been below the range. The 2.5 percent below the range, however, is not a concern if it is below the threshold. The concern is only the 2.5 percent chance that it had a yield above the threshold. For the purposes of monitoring a threshold, this would only be the half of the 5 percent above the threshold, or in other words 2.5 percent. Consequently, the 95 percent confidence level really corresponds to a 97.5 percent confidence level for monitoring violations of a threshold. Following the same argument, the 50 percent confidence level really corresponds to a threshold monitoring at the 75 percent confidence level, and so on.

From the previous discussions, it is obvious that while it may be convenient to chose a particular confidence level to compare monitoring systems (such as the 95 percent confidence level), it should only be done with great caution. In particular, it should be kept in mind that:

- the choice of any particular confidence level is arbitrary, in the sense of being only a convenience to allow comparison of the accuracies of different yield estimation methods;
- as seen from table 1-1, differences can be made to look small or large depending on which particular confidence level is chosen; and
- although very high confidence levels have large ranges of uncertainty, it is with decreasing likelihood that the actual value will be at the extremes of those ranges of uncertainty.

These considerations are important to ensure that common mistakes are not made, namely that:

- the range of uncertainty is not equated with a range in which cheating can occur, and
- the range of uncertainty chosen for comparative reasons does not evolve into the range of uncertainty that is used to determine what constitutes adequate verification.

The Relationship Between Uncertainty and Cheating Opportunities

The main reason for designing monitoring systems with low uncertainty is to reduce the opportunities for cheating. The relationship between uncertainty and opportunities for cheating, however, is not always straightforward. Even if the uncertainty of a particular monitoring system is large, this does not mean that the opportunities for cheating are correspondingly large.

As mentioned before, the uncertainty is created by two types of error: random and systematic. Although we try to estimate the systematic error (such as path bias) as accurately as possible, there is a chance that our estimates could be slightly too high or too low. For example, if our estimate of the bias[5] is too low, we would overestimate the yields of Soviet explosions, and Soviet testing near 150 kt would appear as a series of tests distributed around a yield value that was above 150 kt. If our estimate of the bias were too high, Soviet testing near 150 kt would appear as a series of tests distributed around a yield below 150 kt. The case where we systematically underestimate Soviet yields and they presume this underestimation is occurring is the only case that provides opportunity for unrecognized cheating. If this were happening, it could happen only to the extent that the systematic effect has been underestimated.

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[5] See chapter 7, "Estimating the Yields of Nuclear Explosions," for an explanation of bias.

As chapter 7 discusses, the systematic part of the uncertainty can be significantly reduced by restricting testing to specific calibrated test sites. If such calibration were an integral part of any future treaty, the concern over systematic errors of this kind should be minimal. The majority of the error that would remain is random. A country considering violating a treaty could not take advantage of the random error because it would be unable to predict how the random error would act.

In early 1987, both the Senate Foreign Relations Committee and the Senate Armed Services Committee held hearings on verification capabilities in their consideration of advice and consent to ratification of the 1974 Threshold Test Ban Treaty and the 1976 Peaceful Nuclear Explosions Treaty. Members of these Committees wanted to know whether seismic methods could adequately measure the size of Soviet underground nuclear tests or whether more intrusive methods were required. The testimony was often confusing due to the various means of representing statistical uncertainties. For the time being, we will analyze only the use of statistics and take as given the underlying information. However, that acceptance is also controversial and is discussed separately in the chapter on yield estimation (chapter 7).

The Department of Defense presented the capabilities of seismic monitoring to the Senate Committee on Foreign Relations on January 13, 1987 and the Senate Committee on Armed Services on February 26, 1987 in the following manner:[6]

> The seismic methods that we currently must rely on to estimate yields of Soviet nuclear detonations are assessed to have about a factor-of-two uncertainty for nuclear tests, and an even greater uncertainty level for Soviet peaceful nuclear explosions.

This uncertainty was then explained as follows:

> This uncertainty factor means, for example, that a Soviet test for which we estimate a yield of 150 kilotons may have, with 95 percent probability, an actual yield as high as 300 kilotons—twice the legal limit—or as low as 75 kilotons.[7]

These statements are misleading in that they create the impression that there is a high probability, in fact, almost a certainty, that the Soviets could test at twice the treaty's limit but we would measure the explosions as being within the 150 kt limit. They imply that a factor of 2 uncertainty means that there is a high probability that an explosion measured at 150 kt could, in actuality, have been 300 kt. Yet as we have seen in the discussion of uncertainty, given a factor of two uncertainty, the likelihood of an explosion with a yield of 300 kt actually being measured (with 95 percent probability) as 150 kt or below is less than 1 chance in 40.

The chances decrease even further if more than a single explosion is attempted. For example, the chance of two explosions at 300 kt both being recorded as 150 kt or less is about 1 in 1,600; and the chance of three explosions at 300 kt or greater being recorded as 150 kt or less would be roughly 1 in 64,000. Thus, it is highly unlikely that explosions could be repeatedly conducted at 300 kt and systematically recorded as being 150 kt or less.

So far we have been looking only at the likelihood that a test will appear as 150 kt or less.

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[6] Testimony of Hon. Robert B. Barker, Assistant to the Secretary of Defense (Atomic Energy) and leader of formal negotiations on Nuclear Test Limitations.

[7] This statement is nearly identical to the wording in the U.S. Department of State, "Verifying Nuclear Test Limitations: Possible U.S.-Soviet Cooperation," Special Report No. 152, Aug. 14, 1986, which states "A factor of two uncertainty means, for example, that a Soviet test for which we derive a 'central yield' value of 150 kt may have, with a 95 percent probability, a yield as high as 300 kt or as low as 75 kt."

From a practical point of view, it must be recognized that the test would not need to look like 150 kt or less; it would only have to appear as though it were within the error of a 150 kt measurement in order to avoid credible assertions of non-compliance. Some could misinterpret this as meaning that a test well above the threshold might have enough uncertainty associated with it so that its estimate might appear to be within the expected uncertainty of a test at 150 kt. They might then conclude that the opportunity to test well above the threshold cannot be denied to the Soviets.

Such a one-sided assessment of the uncertainty is extremely misleading because it assumes all of the errors are systematic and can be manipulated to the evader's advantage. A country considering violating the threshold would also have to consider that even if part of the systematic uncertainty could be controlled by the evader, the random part of the uncertainty could just as likely work to its disadvantage. This point was briefly recognized in the following exchange during a Senate Committee on Foreign Relations hearing:

> " . . . knowing these probabilities, if you really started to cheat, as a matter of fact you would take the risk of being out at the far tail. That would really show up fast. If you set out to do a 300 kt, you could show up on our seismographs as 450, right?"
>
> Senator Daniel P. Moynihan

> "The problem is, if you fired an explosion at 300 or 350 . . . it could very well look 450 or 500 and the evader has to take that into consideration in his judgment."
>
> Dr. Milo Nordyke,
> Director of Verification
> Lawrence Livermore
> National Laboratory

Also, this analysis assumes that only one method of yield estimation will be used. Other methods of yield estimation are also available and their errors have been shown to be only partially correlated. The evader would have to take into account that even if the uncertainty is known and can be manipulated for one method of yield estimation, other methods might not behave in the same manner. Such considerations would severely diminish the appeal of any such opportunity.

In conclusion, it can be seen that although the statistical descriptions of the capabilities of various methods of yield estimation have been debated extensively, the differences they represent are often insignificant. There is both systematic and random uncertainty in the measurements of Soviet yields. The systematic error would provide only a limited opportunity for cheating, and then only if it was in the advantage of the cheater. Even in such a case, only the portion of the error that is systematic can be exploited for cheating. Furthermore, much of the systematic error would be removed through such treaty provisions as calibrating the test site. Once the systematic error had been nearly eliminated, the remaining uncertainty would be random. The random uncertainty does not provide opportunity for cheating. In fact, if a country were considering undertaking a testing series above the threshold, it would have to realize that the random uncertainty would work against it. With each additional test, there would be a lesser chance that it would be recorded within the limit and a greater chance that at least one of the tests would appear to be unambiguously outside the limit.

What Constitutes Adequate Verification?

After the accuracies and uncertainties of various verification systems have been understood, a decision must be made as to what constitutes an acceptable level of uncertainty. In 1974, when the Threshold Test Ban Treaty was first negotiated, a factor of 2 uncertainty was considered to be the capability of seismic methods. At that time, a factor of 2 uncertainty was also determined to constitute adequate verification.[8] Presently, the level of accuracy claimed

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[8] Originally, the factor of 2 uncertainty was established for the 90 percent confidence level, whereas today it refers to the 95 percent confidence level. It should be noted that a factor of 2 at the 90 percent confidence level corresponds to about a factor of 2.5 at the 95 percent confidence level. Thus the accepted level of uncertainty in 1974 was really about a factor of 2.5 using the present confidence level. The insistence on a

(continued on next page)

for the on-site CORRTEX method is a factor of 1.3.[9] This level of 1.3 has subsequently been defined as the new acceptable level of uncertainty, although many believe it was defined as such only because it corresponds to the capabilities of this newly proposed system.

It appears that the determination of adequate compliance is a subjective process that has been influenced by the capabilities of specific monitoring systems. A decision as to what constitutes adequate verification should not be determined by the political attractiveness of any particular monitoring system, but rather it should represent a fair assessment of the protection required against non-compliance. In the frozen river analogy, this would be a fair assessment of how thin the ice must be to deter someone from crossing. Monitoring capability certainly influences our decision as to whether a treaty is worthwhile, but it should not influence the standards we set to make that decision. Also, the capability of a monitoring system is just one aspect to be considered, along with other important issues such as negotiability and intrusiveness.

What constitutes adequate verification may also vary for different treaty threshold levels. For example, a factor of 2 uncertainty for monitoring a 100 kt threshold would mean that 95 percent of the measurements at the threshold limit would be expected to fall within 50 and 200 kt (a total range of 150 kt), while a factor of 2 uncertainty for monitoring a 1 kt threshold would mean that 95 percent of the measurements at the threshold limit would be expected to fall within½ and 2 kt (a total range of 1.5 kt). A range of uncertainty of 1.5 kt may not provide the same opportunities or incentives for cheating as a range of uncertainty of 150 kt. Consequently, at lower treaty thresholds, the significance of a given yield uncertainty will almost certainly diminish.

THE QUESTION OF DETERMINING COMPLIANCE

In addition to understanding the accuracy and uncertainty of the verification system, and deciding on an acceptable level of uncertainty, a decision will also have to be made as to what would constitute compliance and non-compliance. Violations of the treaty must be distinguished from errors in the measurements (both systematic and random) and errors in the test. This is of particular concern in light of findings by the administration that:

> Soviet nuclear testing activities for a number of tests constitute a likely violation of legal obligations under the Threshold Test Ban Treaty.[10]

To examine the context in which this must be viewed, we can once again return to the frozen river analogy and imagine a situation where we come by and see marks on the ice. We must then determine whether the marks indicate that someone successfully crossed the ice. This could be misleading because all that we are doing is looking in isolation at the probability that a certain mark could have been made by someone crossing the ice. Thus the likelihood that a mark was made by a person becomes the likelihood that someone crossed the ice. This, however, is only part of the issue. If we knew for example that the ice were so thin that there was only a 1 in 10 chance it could have been successfully crossed, that the water was deep, and that there was no reason to get to the other side, these factors might weigh in our determination of whether a mark was man-made or not. (Why would a person have taken such risks to gain no value?) On the other hand, if we knew the ice were thick and could be crossed with high confidence, that the water was shallow, and that real value was to be obtained by crossing, then we might

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(continued from previous page)

higher confidence level occurred simply because it was more convenient to use the 95 percent confidence level which corresponds to 2 standard deviations.

[9] See appendix, Hydrodynamic Methods of Yield Estimation.

[10] "The President's Unclassified Report on Soviet Noncompliance with Arms Control Agreements," transmitted to the Congress Mar. 10, 1987.

make a different judgment as to whether the marks were man-made because there would really be understandable motivation. Thus the question of compliance is also dependent on a judgment reflecting one's perception of the advantages that could be obtained through a violation.

In the case of test ban treaties, there are also "gray areas" due to the associated error of the measurements. For example, it must be assumed that a country will test up to the limit of the treaty, and therefore, some of the estimates would be expected to fall above 150 kt simply due to random error.[11]

Assuming that the errors are known and that apparent violations of the treaty due to such errors are recognized, there may also be other violations that cause concern but do not negate the benefits of the treaty. These include accidental violations, technical violations, and violations of the "spirit" of the treaty.

Accidental violations are violations of the treaty that may occur unintentionally due to the inexact nature of a nuclear explosion. It is possible that the explosion of a device with a yield that was intended to be within the limit of the treaty would produce an unexpectedly higher yield instead. This possibility was recognized during negotiations of the TTBT. The transmittal documents which accompanied the TTBT and the PNE Treaty when they were submitted to the Senate for advice and consent to ratification on July 29, 1976 included the following understanding recognized by both the United States and Soviet Union:

> Both Parties will make every effort to comply fully with all the provisions of the TTB Treaty. However, there are technical uncertainties associated with predicting the precise yields of nuclear weapon tests. These uncertainties may result in slight, unintended breaches of the 150 kt threshold. Therefore, the two sides have discussed the problem and agreed that: (1) One or two slight, unintended breaches per year would not be considered a violation of the Treaty; (2) such breaches would be a cause for concern, however, and, at the request of either Party, would be subject for consultations.

Technical violations are violations of the treaty that do not result in any sort of strategic advantage. An example would be a technical violation of the 1963 Limited Test Ban Treaty (LTBT) which prohibits any explosion that:

> . . . causes radioactive debris to be present outside the territorial limits of the State under whose jurisdiction or control such explosion is conducted.[12]

This prohibition includes the venting of radioactive debris from underground explosions. Both the United States and the Soviet Union have accused each other of releasing radioactive material across borders and of violations of the 1963 LTBT. These violations are "technical" if the treaty is viewed as an arms control measure. However, they are material violations if the treaty is viewed as an environmental protection measure.

Violations of the "spirit" of the treaty are also of concern. These include, for example, actions which are contrary to the treaty's preamble. The treaty's preamble declares the intentions and provides a context for the treaty. Such declarations, however, are nonbinding.

Another area concerns treaties that have been signed but never ratified. Both the 1974 TTBT and the 1976 PNE Treaty remain unratified, although they were signed over 10 years ago. Because neither the United States nor the Soviet Union have indicated an intention *not* to ratify the treaties, both parties are obligated under international law (Article 18, the 1969 Vienna Convention on the Law of Treaties) to refrain from acts which would defeat their objectives and purposes.

All of these types of violations contribute to the gray area of compliance versus noncompliance and illustrate why determining compliance is a political as well as a technical decision. In the case of monitoring underground nuclear tests, the actual measured yield that would constitute clear evidence of a violation would always be higher than the yield limit of the treaty. Perhaps an analogy for uncertainties in yield estimates and Soviet compliance under the TTBT is in monitoring a speed limit of 55 mph. Under the present 150 kt limit, an observed yield of 160 kt is like comparing 58.7 mph to 55 mph. The police do not give tickets when their radar shows a speed of 58.7 mph because most speedometers are not that accurate or well calibrated, and because curves and other factors can lead to small uncertainties in radar estimates of speed. Similarly, although a 160 kt measurement may be regarded by some as a legal lack of compliance, such a number can well arise from uncertainties in seismic estimates. At radar measurements over 65 mph the police do not question that the 55 mph limit has been exceeded, and the speeder gets a ticket. With this standard, it would take a calculated yield of about 180 to 190 kt to conclude that a violation had likely taken place. As mentioned before, however, this argument does not mean that the Soviets could test up to 180 to 190 with confidence, because the uncertainty could just as likely work against them. A 180 to 190 kt test might produce an observed yield well over 200 kt just as likely as it might produce a yield within the expected error range of a treaty compliant test.

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[11] For example, if the Soviet Union tested 20 devices at 150 kt and we estimated the yields using a system that was described as having a factor of 2 uncertainty, the probability of measuring at least one of them as being 225 kt or greater is 92 percent.

[12] Article I.b.

It must be recognized, however, that the calculated yield for declaring a treaty violation will always be higher than the limit of the treaty. Consequently, one or two small breaches of the treaty could occur within the expected uncertainty of the measurements. A country intent on cheating might try to take advantage of this by risking one or two tests within the limits of the uncertainty range. Even if detected, a rare violation slightly above the permitted threshold could be explained away as an accidental violation due to an incorrect prediction of the precise yield of the nuclear test. This should be kept in mind when choosing a threshold so that small violations of the limit (whether apparent or real) do not fall in a range that is perceived to be particularly sensitive.

What is done about violations is an additional problem. In domestic law there are various kinds of violations. Traffic tickets, misdemeanors, felonies, capital crime—all are different levels. Similarly, in monitoring compliance, there are some things that amount to traffic tickets and some that amount to felonies. We must decide in which cases violations or noncompliance are at the heart of a treaty and in which cases they are a marginal problem.

Chapter 3

The Role of Seismology

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Chapter 3

The Role of Seismology

Seismology provides a technical means for monitoring underground nuclear testing

INTRODUCTION

Verifying a ban on nuclear testing requires global monitoring systems capable of detecting explosions in the atmosphere, under water, and below ground. Tests in the atmosphere and under water can be readily detected with high degrees of confidence. The atmosphere is monitored effectively with satellites containing sensors that can detect the visible and near-infrared light emitted by a nuclear explosion. The oceans can also be monitored very effectively because water transmits acoustic waves efficiently. Underwater explosions would be detected by the acoustic sensors already in place as part of anti-submarine warfare systems. The most uncertain part of the global verification system is the monitoring of underground nuclear explosions that might be conducted within the Soviet Union. The main technical tools for monitoring underground nuclear explosions come from the field of seismology, which is the study of earthquakes and related phenomena.

THE CREATION OF SEISMIC WAVES

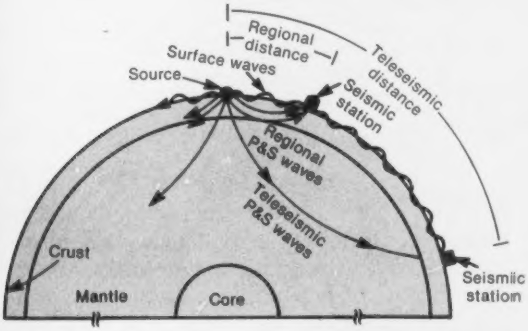
A nuclear explosion releases its energy in less than 1/1,000,000 of a second (a microsecond). The explosion initially produces a gas bubble containing vaporized rock and explosive material. Within a microsecond, the temperature within the bubble reaches about 1 million degrees and the pressure increases to several million atmospheres. A spherical shock wave expands outward from the bubble into the surrounding rock, crushing the rock as it travels. As the hot gases expand, rock is vaporized near the point of the explosion and a cavity is created.

While the cavity is forming, the shock wave continues to travel outward into the surrounding medium. Eventually, the shock wave weakens to the point where the rock is no longer crushed, but is merely compressed and then returns (after a few oscillations) to its original state. These cycles of compression and relaxation become *seismic waves* that travel through the Earth and are recorded by seismometers. By looking at seismic records (seismograms) and knowing the general properties of the travel paths of various waves, seismologists are able to calculate the distance to the seismic event and what type of motion caused the wave.

TYPES OF SEISMIC WAVES

As with earthquakes, seismic waves resulting from an explosion radiate outward in all directions (figure 3-1). These waves travel long distances either by passing deep through the body of the Earth (*body waves*), or else by traveling along the Earth's surface (*surface waves*). The body and surface waves that can be recorded at a considerable distance (over 2,000 km) from the earthquake or explosion that created them are referred to by seismologists as

Figure 3-1.—Seismic Waves Propagating Through the Earth



An earthquake or underground explosion generates seismic waves that propagate through the Earth.

SOURCE: Office of Technology Assessment, 1988.

teleseismic waves. Teleseismic body and surface waves are important to monitoring because to be recorded they do not usually require a network of seismometers near the source. This allows for seismometers to be located outside the region that is being monitored.

Teleseismic waves contrast with what seismologists call *regional waves*. Regional waves are seismic waves that travel at relatively high frequencies within the Earth's crust or outer layers and typically are observed only at distances of less than 2,000 km. Regional waves are therefore recorded at seismic stations that, for application to monitoring Soviet nuclear explosions, would have to be located within the territory of the Soviet Union. Such stations are called *in-country* or *internal* stations.

When seismic waves reach a seismic station, the motion of the ground that they cause is recorded by seismometers. Plots of the wave forms are called *seismograms*. Because the different waves travel at different speeds and along different routes, they arrive at seismic stations at different times. The farther away the seismic station is from the source of the waves, in general, the more dispersed in time the different arrivals will be. By studying seismograms, seismologists are able to recognize the various types of waves produced by events such as earthquakes and nuclear explosions.

TELESEISMIC WAVES

The various types of teleseismic waves are differentiated by both the paths along which they travel and the type of motion that enables them to propagate. The two main subdivisions (body waves and surface waves) are distinguished by the areas through which they travel.

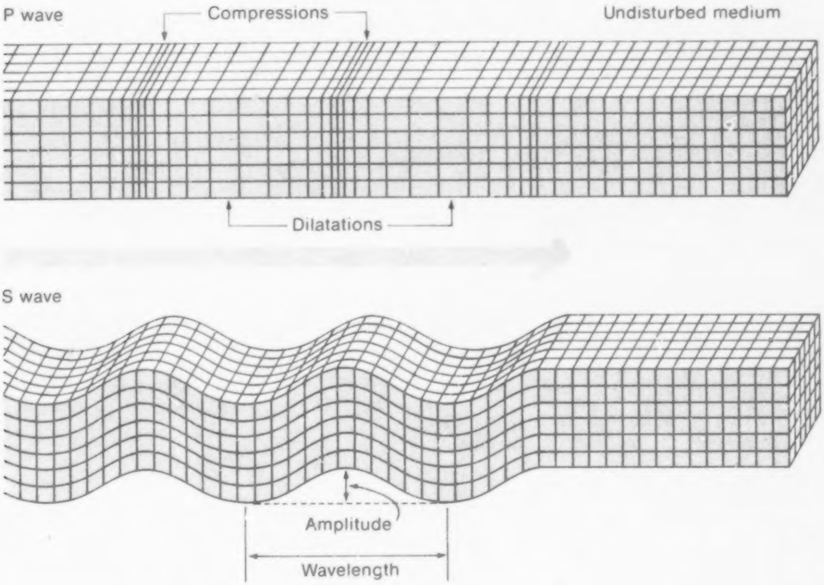
Body Waves

The waves traveling through the body of the Earth are of two main types: *compressional waves* (also called *P waves*) and *shear waves* (also called *S waves*). The designations P and S are abbreviations originally referring to primary and secondary arrivals; compressional waves travel faster than shear waves and, consequently, arrive first at a recording station. Apart from their different speeds, P waves and S waves also have different characteristics.

P waves travel in a manner similar to sound waves, that is, by molecules "bumping" into each other resulting in compression and dilation of the material in which they propagate. A cycle of compression moves through the Earth followed by expansion. If one imagined a particle within the wave, its motion would be one of shaking back and forth in the direction of propagation in response to the alternating compressions and expansions as the wave trains move through. The particle motion is in the direction of travel and the wave can propagate through both solids and liquids. A sudden push or pull in the direction of wave propagation will create P waves (figure 3-2a).

In contrast, S waves propagate by molecules trying to "slide" past each other much as happens when one shakes a rope from side to side and the disturbance passes down the rope. The

Figure 3-2.—Body Waves



Waves traveling through the body of the Earth are of two main types: compressional waves (P waves) and shear waves (S waves).

SOURCE: B.A. Bolt, *Nuclear Explosions and Earthquakes*, W.H. Freeman & Co., 1976.

wave motion is at right angles to the direction of travel. Any particle affected by the wave would experience a shearing motion as the wave passed through. Because liquids have little resistance to shearing motion, S waves can only pass through solid materials. (Liquids can be compressed, which is why P waves can travel through both solids and liquids.) A sudden shearing motion of a solid will result in S waves that will travel at right angles to the direction of propagation (figure 3-2b).

In a P wave, particle motion is longitudinal in the direction of propagation, thus there can be no polarization of a P wave. S waves, however, being transverse, are polarized and can be distinguished as either horizontal or vertical. Particle motion in an *SH wave* is horizontal. In an *SV wave*, particles oscillate in a vertical plane perpendicular to the path.

An underground explosion creates a uniform pressure outward in all directions. Therefore, explosions should be a source of nearly pure P waves. In practice, however, some S waves are also observed. These waves are usually due to asymmetries of the cavity or the pressure within the cavity created by the explosion, structural inconsistencies in the surrounding rock, or the presence of pre-existing stresses in the host rock that are released by the explosion. An earthquake, on the other hand, is generally thought of in terms of blocks of the Earth's crust breaking or slipping past one another along a fault region. Because of the shearing motion, an earthquake creates mostly S waves. P waves are also generated from an earthquake, but only in a four-lobed pattern that reflects the opposite areas of compression and expansion caused by the shearing motion (figure 3-3). As discussed in chapter 5, this difference in source geometry can be used as a means of distinguishing the seismic signals caused by explosions from the seismic signals generated by earthquakes.

Figure 3-3.—Seismic Radiation Patterns

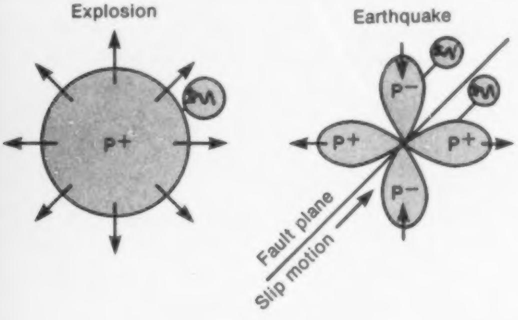
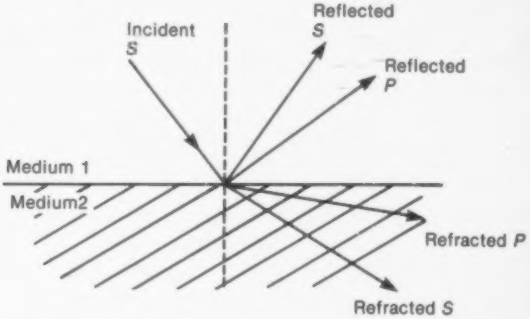


Figure 3-4.—Reflected and Refracted Waves



When a wave hits a boundary within the Earth both reflected and refracted waves can be generated.

The pattern of seismic body waves generated by a given source becomes complicated when the waves interact with the structures of the Earth. In general, when a wave hits a boundary within the Earth, such as where two different rock types meet, both reflected and transmitted P and S waves are generated at several different angles. (figure 3-4)

Because of all these possibilities, P waves and S waves break into many types as they travel through the Earth. At a depth of 30 to 60 kilometers in the Earth, the velocity with which sound passes through the Earth increases markedly. This discontinuity, called the *Mohorovičić Discontinuity* (Moho), serves as a wave guide to trap seismic energy in the upper crust of the Earth.

Surface Waves

At the Earth's surface, two additional seismic wave types are found. These surface waves, called *Rayleigh waves* and *Love waves*,[1] are produced by constructive interference of body wave energy in the upper layers of the crust.

The particle motion of Rayleigh waves is somewhat analogous to that of ripples spreading over the surface of a lake. The analogy is not exact, however, because unlike a water wave, the orbital motion of a particle in a Rayleigh wave is retrograde to the path of wave propagation (figure 3-5a). The energy of the Rayleigh wave is trapped near the ground surface, so as depth increases, the rock particle displacements decrease until, ultimately, no motion occurs.

The second type of surface wave which travels around the Earth is called a Love wave. Love waves have a horizontal motion that is shear, or transverse, to the direction of propagation (figure 3-5b). It is built up of trapped SH waves and has no vertical motion.

While Rayleigh waves can be detected by seismometers sensitive either to vertical or horizontal motion of the Earth's surface, Love waves are only detected by seismometers sensing horizontal motions.

Surface waves of either type, with a period of 10 seconds, travel with a velocity of about 3 kilometers per second. This corresponds to a wavelength of about 60 kilometers. Because of this long wavelength, surface waves are much less likely to be affected by small-scale variations in Earth structure than short period body waves. This makes the use of surface waves attractive for measuring yields of Soviet tests. Body waves (P waves and S waves) are faster than surface waves and therefore arrive first at a recording station. This is fortunate because the surface waves have larger am-

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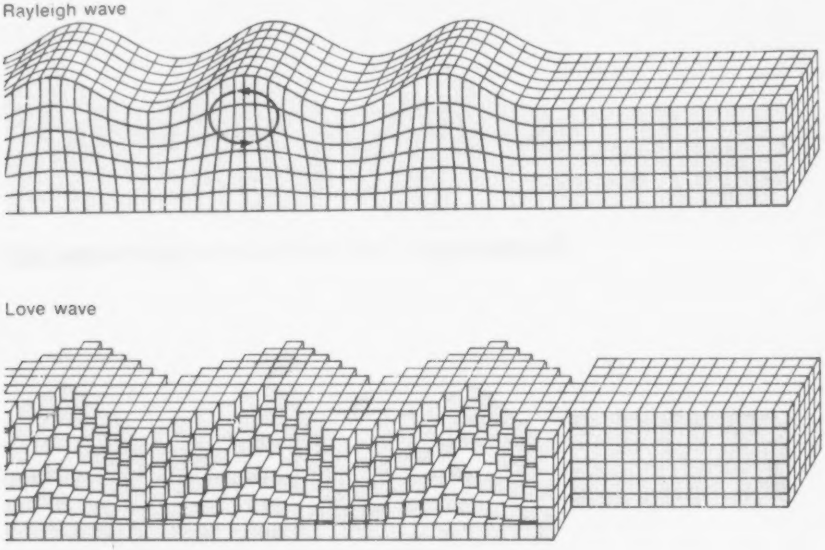
[1] These waves are named after the mathematicians who first developed the theory to describe their motion (Lord Rayleigh and A.E.H. Love).

Figure 3-5.—Surface Waves



Waves traveling along the surface of the Earth are of two main types: Rayleigh waves and Love waves.
SOURCE: B.A. Bolt, *Nuclear Explosions and Earthquakes*, W.H. Freeman & Co., 1976.

plitudes than the body waves. If they all arrived simultaneously, the smaller amplitude P waves would be hidden by the surface waves unless the records were filtered to take advantage of the different frequency content of the two types of waves (figure 3-6).

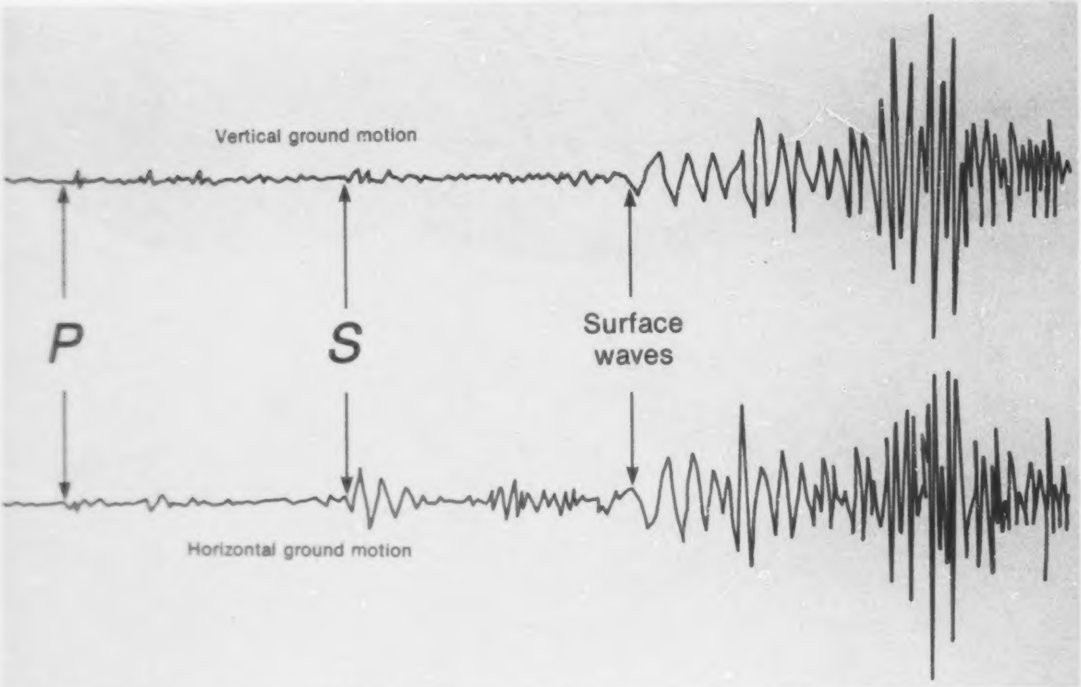
REGIONAL WAVES

In contrast with the teleseismic waves described above, regional waves are usually observed only at distances of less than 2,000 km. In general they have larger amplitudes and higher frequency content then waves from the same source recorded at teleseismic distances. Depending on their propagation characteristics, such regional waves are denoted by P_n, P_g, S_n, and L_g. A comparison of teleseismic and regional seismic waves is illustrated in figure 3-7. Note the different time scales. The amplitude scales are also different.

At regional distances, P_n is usually the first wave to arrive at any given station. It is a wave that goes down through the crust of the Earth, then travels mostly horizontally near the top of the upper mantle (in contrast to the usual body, which goes deeply within the mantle), and finally travels upward through the crust, where the receiver is located. This path is shown in the upper part of figure 3-8. In the lower part are shown some of the multiple bounces that also contribute to the P_n wave. The Moho marks the boundary between the crust and the upper mantle.

P_g is a wave that comes in later than P_n, and travels the path between source and receiver wholly within the Earth's crust. As shown in

Figure 3-6.—Seismograph Recording of P, S, and Surface Waves From a Distant Earthquake



SOURCE: Modified from F. Press and R. Seiver, *Earth*, W.H. Freeman & Co., San Francisco, 1974.

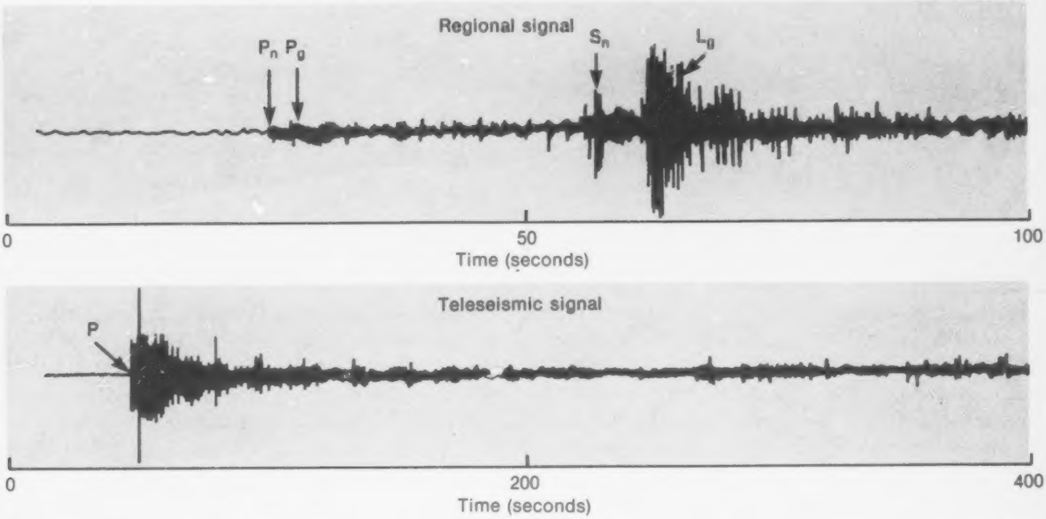
figure 3-9. P_g is thought to be guided by a boundary layer within the crust. It does not propagate to as great a distance as P_n.

S_n is a shear wave that travels a path very similar to that of P_n, but arrives later. S_n arrives later because it is composed of shear waves, which propagate slower than the P waves that make up P_n.

For purposes of explosion monitoring, L_g can be the most important of the regional waves because it is typically the largest wave observed on a seismogram at regional distances. L_g is a type of guided shear wave that has most of its energy trapped in the Earth's crust. In fact, this wave can be so strong that (contrary to what is implied by its inclusion in the class of "regional waves") L_g for a large explosion can be observed even at teleseismic distances, i.e. well in excess of 2,000 km. The observation of L_g out to teleseismic distances, however, can only occur across continents. Beneath an ocean, where the crust is much thinner, L_g fails to propagate even short distances.

Figure 3-10 illustrates how the L_g wave propagates. At the top is shown a seismic source within the Earth's crust. Energy departing downward is partially reflected in the crust and partially transmitted down into the mantle. However, for waves that travel in the more horizontal direction, as shown in the middle part of the figure, energy cannot get into the mantle and is wholly reflected back into the crust. The type of reflection occurring here is the total internal reflection that is similar to that occurring within the prisms of a pair of binoculars. For a fixed source and receiver, there may be many reflection paths, all totally

Figure 3-7.—Regional and Teleseismic Signals



Upper seismogram is of a "regional distance" from the source. Signals here are associated with waves that propagate in the crust and upper most mantle. Lower seismogram is of a "teleseismic distance." This wave has propagated through the deep interior of the Earth.

SOURCE: Modified from Defense Advanced Research Projects Agency.

Figure 3-8.—P_n Wave

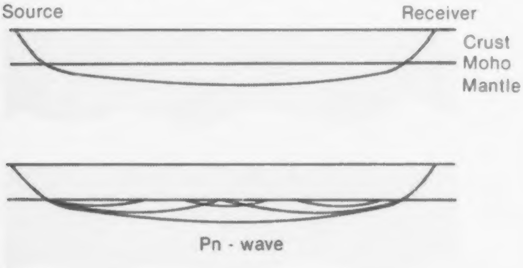

Source
Receiver
Crust
Moho
Mantle
Pn - wave

Figure 3-9.—P_g Wave

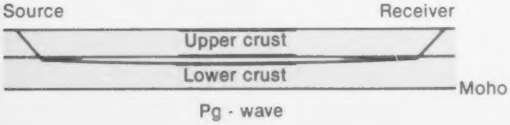
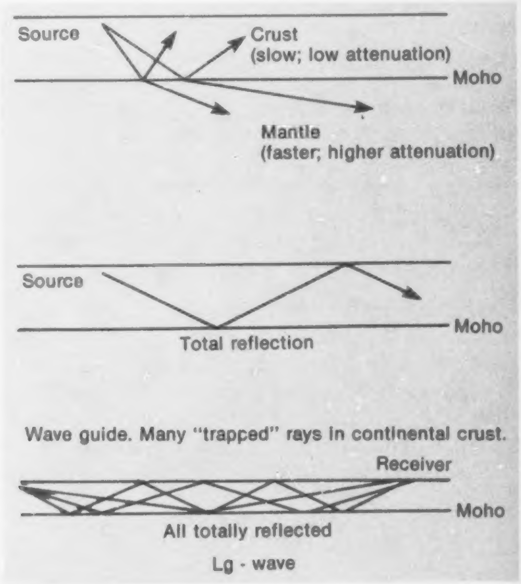

Source
Receiver
Upper crust
Lower crust
Moho
Pg - wave

Figure 3-10.—L_g Wave


Source
Crust
(slow; low attenuation)
Moho
Mantle
(faster; higher attenuation)
Source
Moho
Total reflection
Wave guide. Many "trapped" rays in continental crust.
Receiver
Moho
All totally reflected
Lg - wave

reflected and thus trapped within the crust. This is illustrated in the bottom of the figure. The L_g wave is composed of the entire family of trapped waves, with the crust acting as a wave guide. For regions in which the crust is composed of material that transmits seismic waves efficiently, L_g may be recorded at distances of thousands of kilometers.

For most of the last 30 years, regional waves have been thought of mainly in the context of monitoring small explosions which may not be detected teleseismically. In recent years, however, L_g has come to be recognized as useful for estimating yields for large explosions, independent of the more conventional body wave and surface wave measurements (see ch. 7).

RECORDING SEISMIC WAVES

Seismic waves are measured at observatories around the world by recording the ground motion. Most observatories have "triaxial" seismometers, meaning that they record ground motion in three directions at right angles to each other. Typically they are oriented north-south, east-west, and vertical. By having all three components, seismologists can reconstruct the complete three-dimensional ground motion from the seismograms.

The principle by which the seismometers work can be thought of as a heavy mass freely supported by a spring from a frame fixed to the Earth. When an earthquake or explosion occurs, seismic waves traveling through the Earth reach the seismometer. The frame is shaken in response to the motion of the wave. Although the frame is displaced by the ground motion, the heavy mass tends to remain stationary because of its inertia. The displacement of the grounded frame relative to the stationary mass is therefore a measure of the ground motion. This movement is then electronically magnified so that displacements as small as 0.00000001 centimeters (the same order as atomic spacings) can be detected.

If the Earth were perfectly still, recording small earthquakes and underground explosions would be easy. However, processes such as the winds, ocean waves, tides, man's activity, and seismic waves generated by earthquakes in other regions continually cause motions of the Earth. All of this motion is sensed by seismometers and recorded. Although seismic instruments are sensitive enough to detect seismic waves generated by even the smallest explosion, it will be seen in the following chapters that naturally occurring background noise levels are the limiting factor in detecting small earthquakes and explosions.

To reduce the background noise caused by wind and other surface effects, seismometers have been designed to fit into torpedo-shaped casings and placed in narrow boreholes at a depth of about 100 meters. These types of stations are currently being used as part of the Regional Seismic Test Network (RSTN). The RSTN is a prototype system designed to evaluate the utility of in-country stations that could be placed within the Soviet Union to monitor a low-yield or comprehensive test ban treaty. A typical high quality installation contains three primary seismometers mounted in mutually perpendicular orientations along with three back-up seismometers (figure 3-11).

The seismometer installation is protected against tampering both electronically and through the inherent ability of the instrument to sense disturbances in the ground. The borehole package sends data to a surface station that contains transmitting and receiving equipment and in some cases to an antenna for satellite communications. Also contained in surface stations that might be used for monitoring are power sources, environmental con-

Figure 3-11.—Seismic Instrumentation

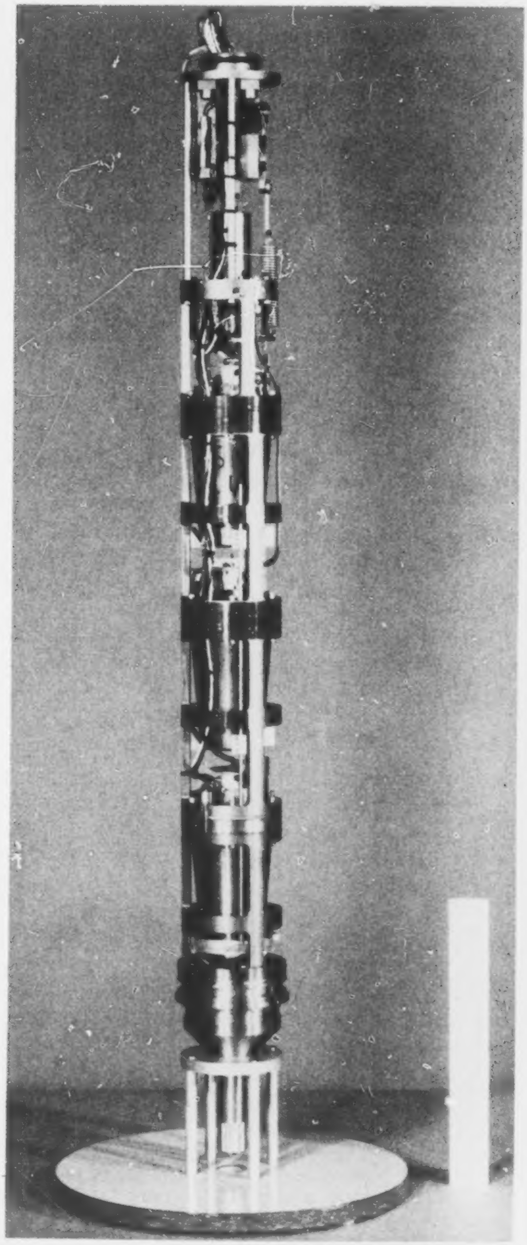
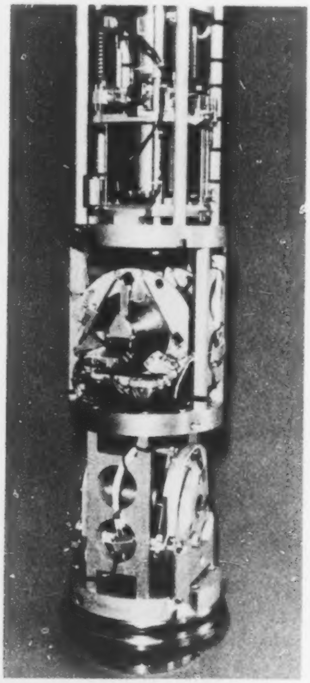
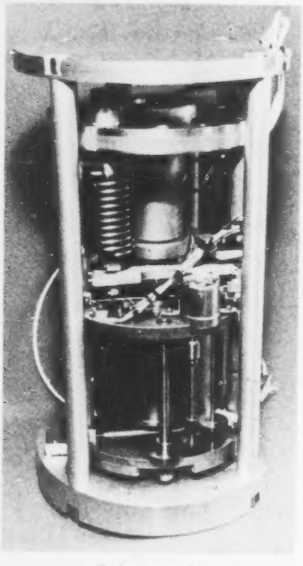


Photo credits: Sandia National Laboratories

Seismic station downhole package containing seismometers, authentication circuits, and processing electronics



Three seismometers mounted in mutually perpendicular orientations



Seismometer

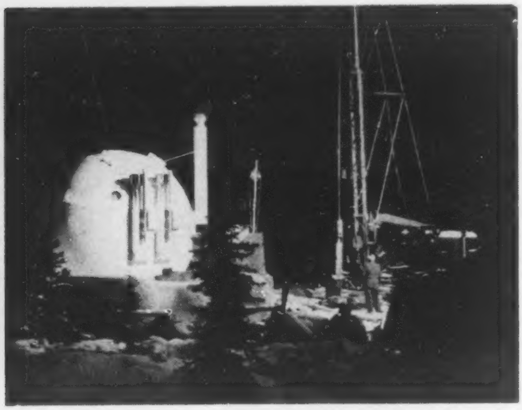
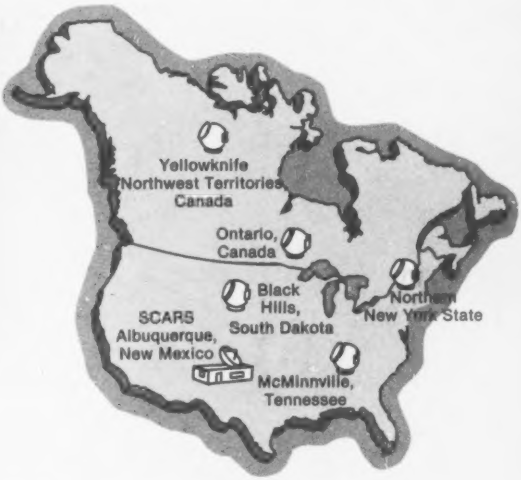


Photo credit: Sandia National Laboratories

An example of what an internal seismic station might look like.

trol apparatus, and tamper-protection equipment. The distribution of six of these stations in North America is designed to simulate the distribution of 10 internal stations within the Soviet Union (figure 3-12).

Figure 3-12.—Distribution of RSTN Stations



Six Regional Seismic Test Network (RSTN) stations are distributed throughout North American to simulate the distribution of 10 internal stations within the Soviet Union.

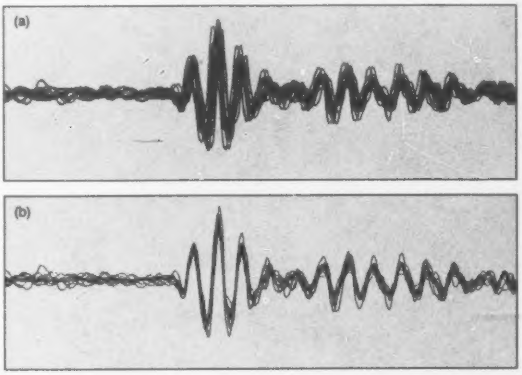
SOURCE: Modified from Sandia National Laboratories.

SEISMIC ARRAYS

The use of *seismic arrays* has been proposed as an alternative and/or supplement to single three-component seismic stations. A seismic array is a cluster of seismometers distributed over a fairly small area, usually on the order of a few kilometers. The signals from the various instruments are then combined to improve the detection and identification of any small or weak signals that may be recorded. Seismic arrays can function like phased array radar receivers, sensitive to waves from a particular direction while excluding waves from other directions. By doing so, arrays can pull small signals out from the surrounding background noise.

To test the application of arrays for monitoring regional seismic events, the United States and Norway installed the Norwegian Regional Seismic Array (NORESS) in 1984. NORESS is located north of Oslo and consists of 25 individual sensors arranged in 4 concentric rings with a maximum diameter of 3 km.

Figure 3-13.—Beamforming



Beamforming is a process of shifting and adding recorded waveforms to emphasize signals and reduce noise. The original waveforms (a) can be shifted to remove propagation delays (b). The signal waveforms are now aligned but the noise is not. The average of the shifted waveforms in (b) would be the beam.

SOURCE: *Energy & Technology Review*, Lawrence Livermore National Laboratory, August 1986, p. 13.

To imagine how an array works, consider an example where a seismic wave is coming from a known location and with a known speed. The time it takes for the wave to travel to each sensor in the array can be predicted from the known direction and speed. In contrast, the seismic background noise will vary randomly from sensor to sensor. The recorded signals from each sensor in the array can then be shifted in time to allow for propagation across the array and combined (figure 3-13). The sensors are close enough so that the signal from the coherent source is nearly the same from each seismometer and remains unchanged. The background noise varies more rapidly and cancels out when the records are added together. Thus, it is possible to suppress the noise relative to the signal and make the signal easier to detect. This process of shifting and adding the recorded waveforms is called *beamforming*. The combination of the shifted waveforms is called the *beam*.

Arrays do, however, have some drawbacks compared to three-component single stations:

1. they are more expensive because they require more hardware and higher installation costs;
2. they require access to a larger area; and
3. they have more sensors that, in turn, generate more data that must be transmitted, stored and processed.

A comparison of the advantages and disadvantages of arrays versus three-component single stations is presented in chapter 4.

Chapter 4

Detecting Seismic Events

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Chapter 4

Detecting Seismic Events

The first requirement for a seismic monitoring network is to detect and locate seismic events that could have been caused by an underground nuclear explosion.

INTRODUCTION

The first requirement for a seismic monitoring network is that it be capable of detecting seismic events. If the Earth were perfectly quiet, this would be easy. Modern seismometers are highly sophisticated and can detect remarkably small motions. However, processes such as the winds, ocean waves, and even rush hour traffic continually shake the Earth. All of this ground movement is sensed by seismometers and creates a background from which signals must be recognized. Seismic networks, consisting of groups of instruments, are designed to detect events like earthquakes and distinguish them from normal background noise. The extent to which a seismic network is capable of detecting events, referred to as the network's *detection threshold*, is dependent on many factors. Of particular importance are the types of seismic stations used, the number and distribution of the stations, and the amount of background noise at the station locations. This chapter reviews these factors and discusses the capability of networks to detect seismic events within the Soviet Union.

THE MEANING OF "DETECTION"

In practical terms, detecting a seismic event means more than observing a signal above the noise level at one station. There must be enough observations (generally from more than one station) to estimate the location of the event that created the detected signal. Measurements of the seismic waves' amplitudes and arrival times must be combined according to standard analytical techniques to give the location and origin time of the event that generated the signal. The event could be any of several natural or man-made phenomena, such as earthquakes, nuclear or chemical explosions, meteorite impacts, volcanic eruptions, or rock bursts.

The seismic signals from these *events* travel from their *source* to individual seismic recording stations along different pathways through a non-uniform Earth. Consequently, no two signals recorded at separate stations will be identical. Even if they came from the same source, the amplitudes, shape, and transit times of the signals would vary according to the path they took through the Earth. This fact has an important impact on the results of the calculations used to determine magnitude and location. The results will never have perfect precision. They will be based on averages and will have associated with them statements of what the possible errors in the most probable solution might be. Origin times and locations of seismic events, the parameters that make up a "detection," are always based on some averaging of the data from individual stations. To determine the origin time, and location of a seismic event, the data from several stations must be brought together at a single place to carry out the required analysis. Seismic stations that routinely send their data to a central location for analysis are said to form a *network*.

The energy radiating from an underground nuclear explosion expands outward. While most of the explosive energy is dissipated by crushing and melting the surrounding rock, a

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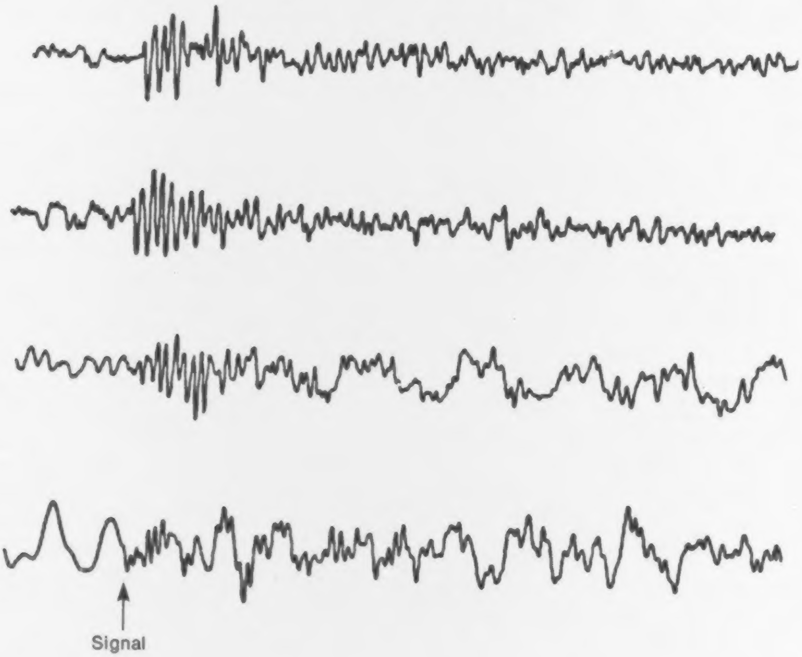
small fraction is transformed into seismic waves. These seismic waves propagate outward and, in so doing, encounter various boundaries and rock layers both at the surface and deep within the Earth. The boundaries cause a separation of the seismic waves into a variety of wave types, some of which travel deep through the interior of the Earth (body waves) and some of which travel along the surface (surface waves). See chapter 3 for a full discussion of wave types and travel paths.

Seismic signals are detected when they are sufficiently above the background noise in some frequency band. Figure 4-1 shows seismograms with standard filters designed to enhance the detection of distant events. In this case, the signal can be seen because it is larger than the noise at high frequency. When data are in digital form (as they are in the latest generation of seismic instrumentation), filters are applied in various frequency bands before detection processing.

Relatively sophisticated techniques can now be used to detect a seismic signal in the presence of noise. In those cases where three perpendicular components of ground motion are recorded using a vertical and two horizontal component seismometers, use can also be made of the known particle motion of P waves to differentiate a P wave signal from background noise. Another technique which can enhance the probability of detecting a signal requires a number of closely spaced seismic sensors known as an array. The data recorded by these sensors can be summed together in a manner which takes account of the expected signal propagation time across the array. The array enhances signals from great distance that prop-

Figure 4-1.—Seismic Signals



Small seismic signals in the presence of seismic noise at four different stations.

SOURCE: U.S. Geological Survey.

agate vertically through the array and can reject noise that travels horizontally. Therefore, the array summation process tends to enhance the signal and to reduce the noise.

For many years, most seismic verification efforts in the United States concentrated on the use of *teleseismic* signals. Teleseismic signals are seismic waves which travel to distances greater than 2,000 km and go deep through the interior of the Earth. Teleseismic waves are used because all seismometers monitoring Soviet testing are located outside the U.S.S.R. and generally at distances which are teleseismic to the Soviet test sites. The possibility of establishing U.S. seismic stations within the U.S.S.R., close to Soviet nuclear testing areas, was discussed seriously as part of negotiations for a Comprehensive Test Ban Treaty. Because techniques for monitoring explosions with *regional* signals were not as well understood as techniques for monitoring with teleseismic data, research efforts to improve regional monitoring greatly increased during the late 1970s. Regional distances are defined to be less than 2,000 kilometers and waves propagating to this distance travel almost entirely through the Earth's outer crustal layers.

LOCATING SEISMIC EVENTS

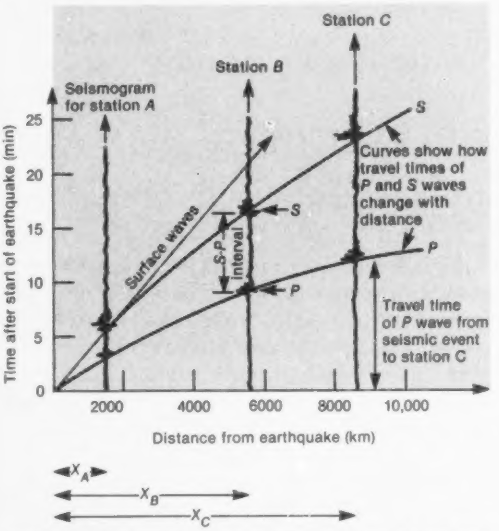
The procedure for estimating the location of a seismic event, using seismic data, involves determining four numbers: the latitude and longitude of the event location, the event depth, and the event origin time. Determination of these four numbers requires at least four separate measurements from the observed seismic signals. These values are usually taken as the arrival time of the P wave at four or more different seismic stations. In some cases, however, determination of the numbers can be accomplished with only two stations by using the arrival times of two separate seismic waves at each station and by using a measure of the direction of the arriving signal at each station. A relatively poor estimate of location can also be obtained using data from only a single array.

The event location process is an iterative one in which one compares calculated arrival times (based on empirical travel-time curves) with the observed arrival times. The differences between calculated and observed arrival times are minimized to the extent possible for each station in the process of determining the location of the seismic event.

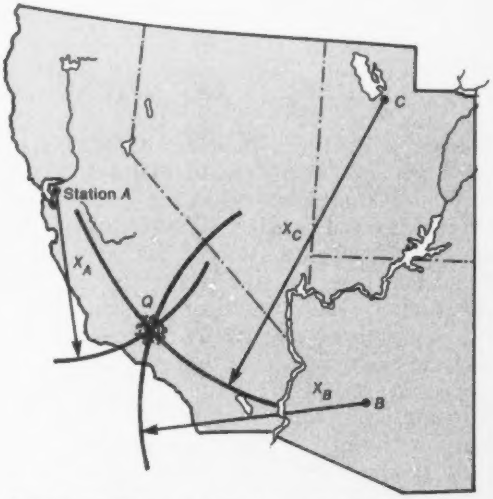
All seismically determined event locations have some error associated with them. The error results from differences between the expected travel time and the actual travel time of the waves being measured and from imprecision in the actual measurements. Generally, these errors are smallest for the P wave (the first signal to arrive), and this is why the capability to detect P waves is emphasized. Location errors are computed as part of the location estimation process, and they are usually represented as an ellipse within which the event is expected to be. Generally, this computation is made in such a way that there is a 95 percent probability that the seismic event occurred within the area of the error ellipse. Thus, location capability estimates are usually given by specifying the size of this error ellipse. Similarly, there is always an uncertainty associated with the measured depth of the event beneath the Earth's surface.

Box 4-A.—Locating A Seismic Event

Estimating the location of a seismic event can be compared to deducing the distance to a lightning bolt by timing the interval between the arrival of the flash and the arrival of the sound of the thunder. As an example, consider the use of the P wave and S wave, where the flash is the first-arriving P wave and the thunder is the slower travelling S wave. The time interval between the arrival of the P wave and the arrival of the S wave (which travels at about half the speed of the P wave), increases with distance. By measuring the time between these two arrivals and knowing the different speeds the two waves travel, the distance from the event to the seismometer could be determined (figure A). Knowing the distance from several stations allows the location to be pinpointed (figure B).



The time required for *P*, *S*, and surface waves to travel a given distance can be represented by curves on a graph of travel time against distance over the surface. To locate an earthquake the time interval observed at a given station is matched against the travel-time curves for *P* and *S* waves until the distance is found at which the separation between the curves agrees with the observed *P-S* time difference. Knowing the distance from the three stations, *A*, *B*, and *C*, one can locate the epicenter as in figure B.



Knowing the distance, say X_A, of an earthquake from a given station, as by the method Figure A, one can say only that the earthquake lies on a circle of radius A, centered on the station. If, however, one also knows the distances from two additional stations *B* and *C*, the three circles centered on the three stations, with radii X_A, X_B, X_C, intersect uniquely at the point Q, the location of the seismic event.

SOURCE: This example is taken from Frank Press and Raymond Seiver, *Earth* (San Francisco, CA: W. H. Freeman and Company, San Francisco, CA, 1974).

DEFINING MONITORING CAPABILITY

Seismic Magnitude

A seismic monitoring system must be able to detect the occurrence of an explosion, to locate the explosion, to identify the explosion, and to estimate the yield of the explosion. The capability of a seismic network to perform each of these tasks is generally described as a function of a measure called the *seismic magnitude* of an event.

Seismic magnitude was first developed as a means for describing the strength of an earthquake by measuring the motion recorded on a seismometer. To make sure that the measurement was uniform, a standard method was needed. The original calculation procedure was developed in the 1930s by Charles F. Richter, who defined local magnitude, M_L, as the logarithm (to the base 10) of the maximum amplitude (in micrometers) of seismic waves observed on a Wood-Andersen torsion seismograph at a distance of 100 kilometers (60 miles) from the earthquake.

Subsequently, the definition of seismic magnitude has been extended, so that the measurement can be made using different types of seismic waves and at any distance. For body waves, the equation for seismic magnitude m_b is:

$$m_b = \log (A/T) + B(d,h),$$

where A is the maximum vertical displacement of the ground during the first few seconds of the P wave, and T is the period of the P wave. The B term is a correction term used to compensate for variations in the distance (d) between the seismic event and the recording station and the depth (h) of the seismic event. For a seismic event at the surface of the Earth, $h=0$. The B correction term has been determined as a function of d and h by observing seismic signals from a large number of earthquakes.

For surface waves, seismic magnitude M_s can be calculated by a similar equation:

$$M_s = \log (A/T) + b \log d + c,$$

where b and c are numbers determined from experience. A number of formulas, involving slightly different values of b and c for M_s, have been proposed.

The terms in both the body wave and surface wave magnitude equations that are used to compensate for distance reflect an important physical phenomenon associated with seismic wave propagate. This phenomenon, referred to as *attenuation*, can be simply stated as follows: *the greater the distance any particular seismic wave travels, the smaller the wave amplitude generally becomes. Attenuation* of wave amplitude occurs for a number of reasons including:

1. the spreading of the wave front over a greater area, thereby reducing the energy at any one point on the wavefront;
2. the dissipation of energy through natural absorption processes; and
3. energy re-direction through diffraction, refraction, reflection and scattering of the wave at various boundaries and layers within the Earth.

As a consequence, a correction term is needed to obtain the same magnitude measurement for a given seismic event from data taken at any seismic station. The correction term increases the amplitude measurement to compensate exactly for the amplitude decrease caused by the different attenuation factors.

Therefore, if the amplitude of the seismic wave is to be used to estimate the size of the seismic event (whether it is an explosion or a naturally occurring earthquake), a good understanding of how amplitude decreases with distance is needed for both body and surface waves. The distance-dependent numbers in the body and surface wave equations represent average corrections which have been developed from many observations. In general, these corrections will not be exact for any one particular path from a particular seismic event to a particular sensor. It is important, therefore, either to calibrate the site to receiver path or to compute the magnitude of the event using seismic signals recorded at a number of well-calibrated stations. If multiple stations are used, the event magnitude is calculated by averaging the individual station magnitudes for an event. From this procedure, an *average* body wave magnitude (m_b) and an *average* surface wave magnitude (M_s) are determined for the event.

Obviously, the distance the wave has traveled must be known to determine the attenuation in amplitude and correct for it. Therefore the seismic event must be located before its magnitude can be determined.

Converting Magnitude to Explosive Yield

The detection and identification capabilities of seismic networks are described most conveniently in terms of seismic magnitudes, typically m_b. This measure is used because m_b is directly related to seismic signal strength. When interpreting capabilities in terms of explosive yield, however, an additional step is required to translate m_b to kilotons. The same magnitude value can correspond to yields that range over a factor of about 10. Variations in the magnitude-yield relationship are caused by variations in the structure of the Earth in the vicinity of the test site (low signal attenuation versus high signal attenuation areas), the material in which the explosion is emplaced (hard, water-saturated rock versus dry, porous materials), and the way in which the explosion is emplaced (tamped versus detonated in a large cavity designed to muffle the signal).

For example, if an explosion is "well-coupled," that is, if the energy is well transmitted from the explosion to the surrounding rock, an m_b of 4.0 corresponds to an explosion of *about* 1 kt. This relationship is true only for explosions in hard rock and may vary considerably depending on how well the seismic waves are transmitted through the area's geology. In areas that are geologically old and stable, seismic waves are transmitted more efficiently. An m_b of 4.0 produced by a well-coupled explosion in an area of good transmission might correspond to an explosion much smaller than a kt. In areas that are geologically young and active, seismic waves are not transmitted as efficiently and an m_b of 4.0 may correspond to a well-coupled explosion larger than 1 kt.

Even greater changes in the relationship between m_b and yield can occur if the explosion is intentionally "de-coupled" from the surrounding rock in a deliberate attempt to muffle the seismic signal. As we will see in chapter 6, decoupling can be accomplished at low yields under some situations by detonating the blast in a large underground cavity. Through such evasion methods, the same 1 kt explosion that produced a magnitude m_b of 4.0 when "well-coupled" might be muffled down to a seismic signal of around m_b 2.0 at low frequencies. Lesser reductions can be accomplished by detonating the explosion in dry porous material.

Because the yield that corresponds to a specific m_b depends so much on the scenario that is being discussed, seismologists generally use seismic magnitude to describe monitoring capabilities. In translating seismic magnitudes to yields, the reader must consider the context in which the comparison is made. In particular, it should be considered whether the explosion is being recorded in an area of good transmission and whether the explosion is well-coupled. Unless specifically stated, this report translates seismic magnitudes to yields corresponding to "tamped" conditions, that is, a well-coupled explosion in hard rock. Situations where decoupling is feasible, and the effects of such decoupling, are discussed in chapter 6.

Seismic Monitoring in Probabilistic Terms

Whether seismic measurements are made by hand or by computer, some error is involved. Even greater additional errors arise from the imperfect estimates of how well seismic waves travel through different parts of the Earth and how well seismic energy is coupled to the Earth during the explosion. All of these errors result in some uncertainty in the final determined parameters. This is true whether these parameters are event magnitude, location, identification characteristics, or yield. In all cases, however, it is possible to estimate a confidence factor in probability terms for the determined parameter. It is important to realize, therefore, that while the numbers are not presented with 100 percent certainty, estimates of the uncertainty are known. In general, this uncertainty is greatest for the small events and decreases for the larger events. A discussion of the uncertainty and what it means in terms of national security concerns is presented in chapter 2.

LIMITATIONS TO SEISMIC MONITORING CAPABILITY

The strength of a seismic signal diminishes with distance. In general, the closer the seismic station is to the source, the stronger the signal will be. Hence, a principal element of monitoring strategy is to get close to areas of concern. It follows that the more high quality stations distributed throughout a given area, the greater the capability will be to detect small events.

Seismic Noise

As noted previously, if the Earth were perfectly still, detecting even the smallest seismic event would be easy. However, the Earth's surface is in constant motion. This motion is the result of many different energy sources. Major storms over ocean areas and the resultant wave action on continental shores cause significant noise in the 2- to 8-second band. Wind noise and noise from atmospheric pressure fronts are particularly prominent on horizontal-component seismic recordings. These more or less continuous motions of the Earth are referred to as *seismic noise* or *microseisms* (figure 4-2). For purposes of siting a seismic station, it is highly desirable to find an area that has a low background level of seismic noise. Generally, the lower the background seismic noise at any station, the smaller will be the seismic signal which can be detected at that station.

Cultural activities can also generate seismic noise that appears in the frequency range used to monitor nuclear explosions. Generally, this man-made noise has frequencies higher than 1 Hz. Heavy machinery, motors, pumping stations, and mills can all generate observable seismic noise. However, careful siting of seismic stations can minimize the problem of most man-made seismic noise. From a monitoring point of view, it is important that noise surveys be made prior to the final selection of sites for seismic stations. If such sites are negotiated within other countries, provisions should be made for relocating the sites should seismic noise conditions change.

Seismic signals and noise are concentrated in various frequency bands. Only the noise within the frequency bands in which seismic signals are observed is a problem. Even strong noise can be eliminated by filtering as long as the noise is outside the detection bands of interest.

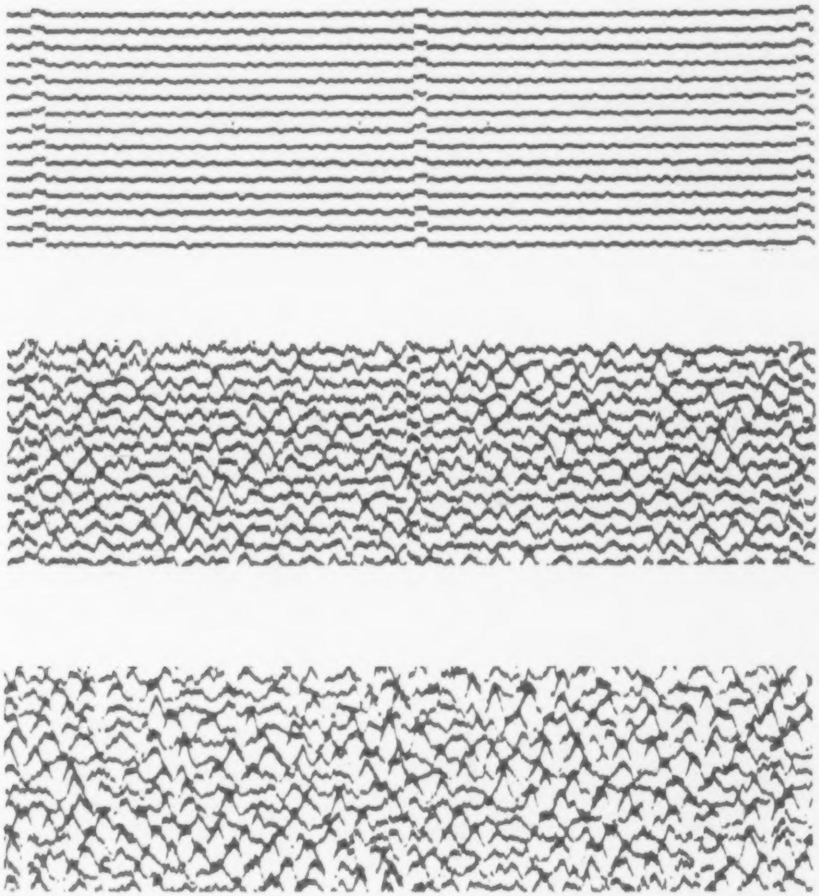
The possibility also exists that a seismic signal from one event can be masked by the seismic signal from another event. While this does indeed happen, it is only a problem for monitoring at yields around 1 kt or less without internal stations. For events of interest in the U.S.S.R. above a magnitude of about m_b 4.0, there are a sufficient number of stations detecting the event so that masking of the signal at a couple of stations generally poses no serious problem. For events much below m_b 4.0, a number of stations at regional distances (distances less than about 2,000 km) would have to be used to avoid the masking problem. Such stations would be available if the United States obtains access to data from seismic stations placed within the U.S.S.R. as part of a negotiated agreement between the United States and the Soviet Union.

Reduction of Signals at Source or Sensor

Poor coupling to the geologic media, either at the explosion source or at the seismic sensor, will act to reduce the amplitude of the seismic signal received. If the explosion is in dense hard rock or in water saturated rock, the source coupling will be good. If the explosion is in alluvium, dry porous rock, or within a cavity, the coupling will not be as good. Decoupling an explosion by detonation within a cavity is an important evasion scenario which will be discussed in chapter 6.

At the seismic sensor, signal reduction can occur if the sensor is not placed on hard rock. In particular, if there is a layer of soil upon which the sensor sits, the signal-to-noise ratio at the sensor can be far less than if the sensor

Figure 4-2.—Seismic Noise



Background seismic noise at three different stations.

SOURCE: U.S. Geological Survey.

were placed on or within hard rock. Sensors placed in boreholes in hard rock provide superior coupling to the Earth and also provide a more stable environment for the instrument packages, with a concomitant reduction in noise.

Seismic Instrumentation

Until recently, the instrumentation that was available for detecting, digitizing, and recording seismic signals did not have the capability to record all the signal frequencies of interest with sufficient range. Further, the mechanical and electronic components comprising seismic recording systems generate internal noise, which is recorded along with true ground noise and seismic event signals, and this internal noise was the limiting factor in recording seismic signals in the high frequency range. Specifically, the internal noise of the older designs of high frequency seismic detectors was higher than ground noise at frequencies above about 5 Hz. Thus, while ground noise is now known to decrease with increasing frequency, the system noise remained constant or increased with increasing frequency in the older systems. Therefore, trade-offs were made, and the entire frequency range of the signal was generally not recorded. Specifically, in the high frequency range data was generally not recorded above 10 Hz and even then was highly contaminated in the 5-10 Hz range by internal system noise. Consequently, small seismic events, particularly small explosions, with expected maximum signal energy in the high frequency range above 5 Hz were not detected because their high frequency signals were below the internal system noise levels. Most existing seismic stations are of this type and so are limited for nuclear test monitoring.

Today, broadband systems capable of recording the entire frequency range with a large dynamic range and with low internal noise are available. However, the best high performance systems are not widely distributed. To establish confident detection-identification capabilities using high frequency seismic signals at low event magnitudes, it will be necessary to expand the number of high performance stations and to place them in diverse geologic environments in order to simulate the requirements of in-country monitoring.

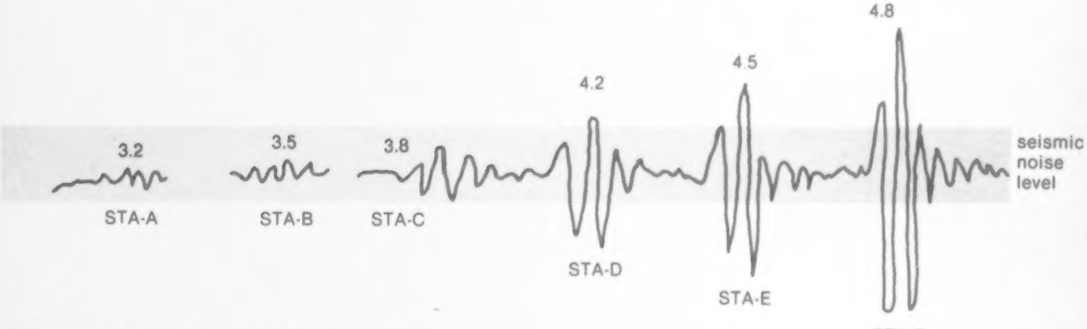
Seismic Magnitude Estimation Problems

As discussed earlier, the estimate of an event's seismic magnitude is made by combining the estimates obtained from many single stations in an averaging procedure to reduce random errors. This procedure works well for an event which is neither too small nor too large.

For a small event, however, the averaging procedure can result in a network magnitude value which is biased high. This follows from the fact that for a small event, the signals will be small. At those stations where signals fall below the noise, the small signal amplitudes will not be seen. Consequently, only higher amplitude values from other stations are available for use in computing the network average. With the low values missing, this network average is biased high unless a statistical correction is made.

Figure 4-3 illustrates this effect. All six stations (A through F) record the same magnitude 4 event. Stations A, B, and C record the

Figure 4-3.—Effect of Noise on Event Magnitude Computation



Average event magnitude = 4.0 (6 stations)

Computed average magnitude = 4.5 (3 stations)

SOURCE: Modified from Air Force Technical Applications Center.

event below average. Stations D, E, and F record the event above average. Normally, the stations would all average out to a magnitude 4.0. For a small event, however, the stations that record low (A, B, & C) do not record the signal because it is below the noise level. Only the stations that record higher (D, E, & F) show the event. Without the values from the low stations, the calculation of the average is made using only the stations that record high. The resulting calculation biases the average to the values of the higher stations, giving a false average magnitude value of (in this example) 4.5 for a 4.0 seismic event.

In the past, computed magnitudes of small events were systematically biased high in this manner. As a result, for most of the last 25 years, the U.S. capability to detect seismic events within the U.S.S.R. has, in fact, been significantly better than the estimates of this capability. Not until the late 1970s was it demonstrated that the small events being detected were 0.2 to 0.4 magnitude units smaller than previously thought. In terms of yield, this means that the networks were actually capable of detecting events down to half as large as previously thought possible. Within the last few years, analysis procedures have been employed to correct for most of this bias using a procedure called *maximum likelihood estimation*.

For large events, a similar bias problem used to exist occasionally, but for a different reason. Old seismometers could not record very large signals without clipping the signal. Larger amplitude signals were either not available or were under estimated. The resulting bias of large events, however, did not affect estimates of detection capability and only became a problem in the determination of the size of very large events.

SEISMIC NETWORKS

Existing Networks and Arrays

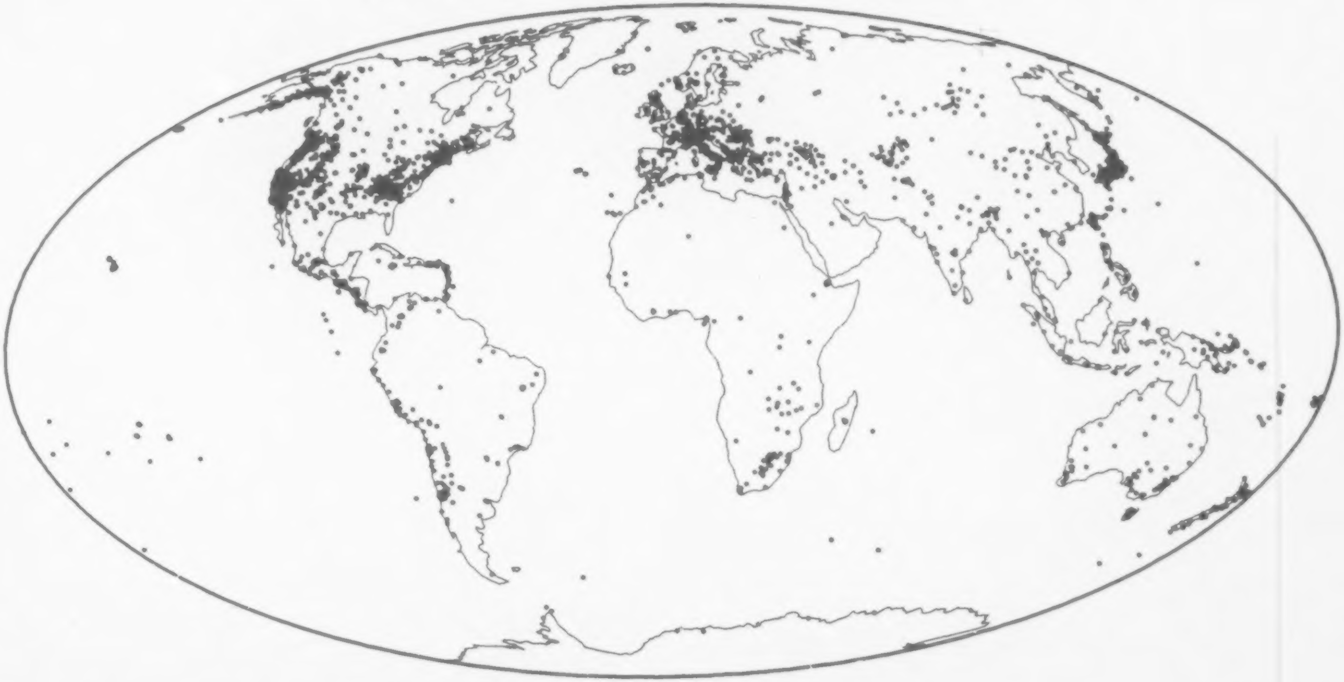
Although many thousands of seismic stations exist around the world, the actual number of stations which routinely report data to national and international data centers is a few thousand. For example, in figure 4-4 the 3,500 stations are shown that routinely report data to the National Earthquake Information Center (NEIC), a center in Colorado operated by the United States Geological Survey. Some of these stations report much more often than do others. The instrumentation at these stations is diverse and the quality of the data varied. While these stations are very useful for seismic signal detection, they are less useful for purposes of magnitude estimation and for research requiring stations evenly distributed around the world.

For purposes of treaty monitoring operations and research, a well distributed network with a common set of instrumentation at all stations is most useful. To obtain such a standard network, the United States funded the development and deployment of the Worldwide Standardized Seismograph Network (WWSSN) in the early 1960s (figure 4-5). The WWSSN is maintained by the United States Geological Survey (USGS). The quality and performance of the WWSSN is generally very good, but the recording system is limited in dynamic range and resolution because of the use of what is now obsolete analog equipment and also because of high internal noise in the amplifying equipment. (For example, the data are currently recorded only on photographic paper records.)

Beginning in the early 1970s, digital recording seismic stations were developed by the United States and other countries. The data from these stations can be easily processed by digital computers to enhance the signal-to-noise for signal detection and to analyze the data for seismic source determination and for research purposes. These stations are included in such networks as:

- The Regional Seismic Test Network (RSTN). These are high quality stations

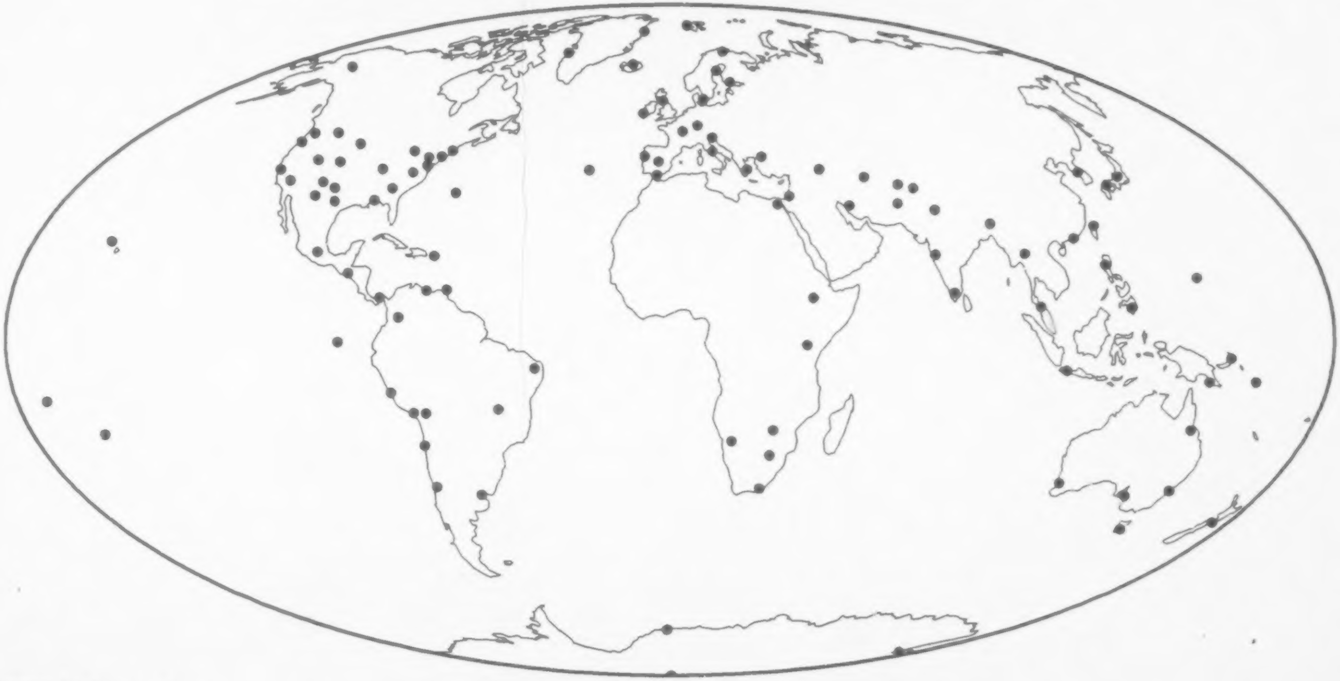
Figure 4-4.—Contributing Seismograph Stations (3,574 stations)



Seismic stations which routinely report data to the USGS National Earthquake Information Center (NEIC).

SOURCE: U.S. Geological Survey.

Figure 4-5.—Worldwide Standardized Seismograph Network (WSSN) Station Distribution



SOURCE: U.S. Geological Survey.

designed by the Department of Energy and now operated by the USGS. They were intended to be prototypes of in-country stations. There are five RSTN stations distributed over North America at interstation distances that represent monitoring in the Soviet Union with 10 internal stations.
- The NORESS seismic array in Norway. This seismic array is funded by the Defense Advanced Research Projects Agency (DARPA) and the Department of Energy (DOE). The prototype array is located in southern Norway, an area thought to be geologically similar to the western part of the Soviet Union.
- The recently installed China Digital Seismic Network (CDSN), which is a cooperative program between the People's Republic of China and the USGS.
- The Atomic Energy Detection System (AEDS) seismic network. This network is operated by the Air Force Technical Applications Center (AFTAC). The purpose of the AEDS network is to monitor treaty compliance of the Soviet testing program. Consequently, the stations are located so as to provide coverage primarily of the U.S.S.R. The capabilities of the AEDS network are described in a classified annex to this report. The USGS and the AEDS stations are the main sources of routine information on Soviet testing.

In addition to these networks, there is also a jointly operated NRDC-Soviet Academy test site monitoring network in the United States and the Soviet Union. The network consists of three stations in each country around the Kazakh and Nevada test sites at distances of about 200 kilometers from the boundaries of each test site. These stations are supplying high-quality seismic signal data, in the high and intermediate frequency range from 0.1 Hz to about 80 Hz. The stations are designed to be modern prototypes of the in-country seismic stations required for monitoring a low threshold test ban treaty and they are not limited by system noise in the high frequency range. Plans call for the addition of five more such stations distributed across the Soviet Union and for several more to be similarly distributed across the United States.

Planned Networks

There are a number of planned new networks that will provide increased capability to detect, locate, and characterize seismic events around the world. These networks are being developed by the United States and other countries.

Hypothetical Networks

Existing unclassified networks external to the U.S.S.R. have an excellent capability for monitoring events with seismic magnitudes greater than 4.0 within the U.S.S.R. However, for explosions less than a few kt, the possibility exists that the seismic signals from such explosions could be reduced through an evasion method. To demonstrate a capability to defeat credible evasion scenarios that could be applied to explosions with yields less than a few kt, seismic stations within the Soviet Union would be necessary.

Obviously, there are a number of requirements for such internal stations and their data. Among these are the following: the data must be provided in an uninterrupted manner; the data must be of high quality; the seismic noise at the stations should be low; the operating parameters of the stations and the characteristics of the data should be completely known at all times; the data should be available to the United States within a reasonable time frame; the stations should be located for effective monitoring of the U.S.S.R.; and any interruption or tampering with the operation of the station should be detectable by the United States. Obviously, these requirements can most easily be achieved by deploying U.S. designed and built seismic stations within the U.S.S.R. at sites chosen by the United States.

The number of stations required within the U.S.S.R. is a function of a number of factors including: the threshold level down to which monitoring is desired, the seismic noise at the stations, the signal-to-noise enhancement capability of the stations, the signal propagation characteristics within the U.S.S.R., and the possibilities for various evasion scenarios thought to be effective within different areas of the U.S.S.R. Many seismologists have proposed distributions of internal stations capable of detecting seismic events down to various thresholds. The number of internal stations proposed for the various distributions ranges between 10 and 50.

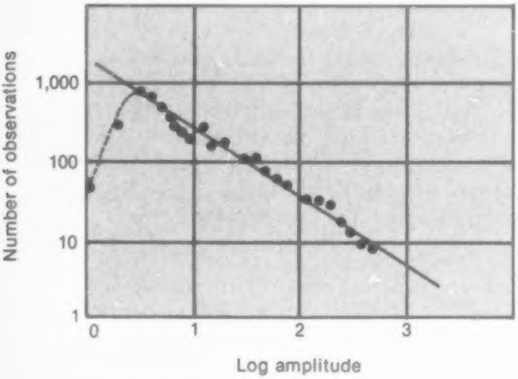
SEISMIC MONITORING CAPABILITY

Calculating Seismic Monitoring Capability

Calculating the detection capability of existing seismic stations is straightforward. For hypothetical stations, however, the detection capability must be estimated by adopting a number of assumptions. Because there exists a range of possible assumptions which can be argued to have validity, there are also a range of possible capabilities for a network of hypothetical internal stations.

For existing stations, the average detection capability is easily determined by observing the number of seismic events detected as a function of log amplitude (figure 4-6). The station can be expected to detect all events within a given region down to some magnitude level. A cumulative plot of the detections, such as illustrated in figure 4-6, will show that a straight line can fit these values down to this magnitude threshold level. This threshold marks the point where the station fails to detect all events. The 90-percent detection threshold (or any other threshold) can be determined from this plot. If the event magnitude rather than the observed amplitude is used, it is important that all magnitudes used in such plots be corrected for low-magnitude bias as previously discussed. By examining all stations of a network in this manner, the station detection parameters can be determined and used to compute overall network performance for the given region.

Figure 4-6.—Detection Capability of a Seismic Station



SOURCE: Modified from Air Force Technical Applications Center.

For hypothetical internal stations, no detection statistics are generally available for computing the cumulative detection curve as a function of magnitude. Therefore, the detection capability must be estimated by assuming the following factors: the seismic noise at the station, the propagation and attenuation characteristics of the region through which the signals will travel, the efficiency of the seismic source, and the signal-to-noise ratio required for the signal to be detected. All the above factors must be evaluated in the frequency range assumed to be best for detecting a signal. The result of all these factors, when considered together, is to provide an estimate of the probability that a signal from a source of a given size and at a given location will be detected at a certain station. Individual station detection probabilities are then combined to determine the overall probability that four or more stations will detect the event. Translating this capability to situations where evasion might take place requires additional considerations (see ch. 6).

Global Detection Capability

There are many seismic stations that exist around the world from which data can be obtained. While no attempt has ever been made to determine the global detection capability of all these stations, a rough estimate could be made by reviewing the various reporting bulletins and lists. However, the current global detection capability does not really matter because it will soon change as various planned networks become installed. Consequently, an accurate assessment of global capability is best addressed by discussing planned networks.

For regions external to the U.S.S.R., and particularly for regions of the Southern Hemisphere, the greatest detection and location capability will reside not with the AEDS, but with a number of existing and planned seismic networks which are unclassified. This is a logical consequence of the AEDS being targeted primarily at events within the U.S.S.R. In particular, national networks such as those of Australia, China, the United States, Italy, and Canada will provide significant global capability.

Given all the national and global data sources, a cautious estimate of the global detection capability by the year 1991 (assuming 90 percent confidence of four or more stations detecting an event using only open unclassified stations) is m_b 4.2. For many regions, such as the Northern Hemisphere, the detection capability will be, of course, much better. Therefore, by 1991, any explosion with a magnitude corresponding to 1-2 kt well-coupled that is detonated anywhere on Earth will have a high probability of being detected and located by networks external to the U.S.S.R. Opportunities to evade the seismic network outside the Soviet Union are limited. Because evasion scenarios require large amounts of clandestine work, they are most feasible within the borders of a closed country such as the Soviet Union. Consequently, monitoring networks are designed to target principally the Soviet Union.

Detection Capability Within the U.S.S.R. Using No Internal Stations

Given that a large range of possible networks exists, a few type examples are useful to convey a sense of what can be accomplished. For example, the capability of a hypothetical network consisting of a dozen or so seismic arrays that are all *outside* the borders of the Soviet Union can be calculated. **A cautious estimate is that if such a network were operated as a high-quality system, it would have 90 percent probability of detecting at four or more stations all seismic events within the Soviet Union with a magnitude at least as low as 3.5. This corresponds to an explosion having a yield below 1 kt unless the explosion is decoupled.**

The hypothetical detection threshold of m_b 3.5 is considered cautious because it is known that a greater detection capability might exist at least for parts of the U.S.S.R. For example, the single large NORSAR array in Norway has the potential to achieve detection thresholds equivalent to an event of m_b 2.5 or lower (corresponding to a well-coupled explosion between 0.1 and 0.01 kt) over large regions of the Soviet Union.[1]

Also, fewer stations (fewer than the four needed above) may detect much smaller events, and this can provide useful information. However, detection by one or a few stations may not be adequate to, with high confidence, locate or identify events. Also, reductions of the detection threshold must be accompanied by a comparable capability to locate the events (for focusing other intelligence resources) and to separate nuclear explosions from earthquakes and legitimate industrial explosions.

Detection Capability Within the U.S.S.R. Using Internal Stations

Seismic stations located internal to a country for the purpose of monitoring have a number of important advantages: improved detection capability, improved location capability, and improved identification capability.

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[1] The potential instantaneous detection thresholds for the large NORSAR array (42 seismometers spread over an area of about 3,000 km^2), as described in "Teleseismic Detection at High Frequencies Using NORSAR Data" by F. Ringdal in *NORSAR Semiannual Technical Summary*, Apr. 1-Sept. 30, 1984, are:

West of Ural Mountains—m_b	2.0-2.5 (possibly better)
Caspian Area—m_b	2.0-2.5
Semipalatinsk—m_b	2.5-3.0
Siberia—m_b	2.5-3.5

Although much debate is associated with the predicted detection capabilities of internal stations, improved detection capability alone is probably not of the greatest significance at this time because the current detection capability is already very good. The improvement that internal stations will provide to *identification* capability (differentiating explosions from natural events) is by far the most important reason for requiring internal stations and should be considered the basic requirement for internal stations. The problem of detecting and identifying seismic events in the face of various evasion scenarios will be discussed in the next two chapters.

Based on cautious assumptions for a network of 30 internal arrays or about 50 three-component internal stations, it appears likely that a detection threshold of m_b 2.5 (90 percent probability of detection at four or more stations) could be reached. This corresponds to a well-coupled explosion of 0.1 - 0.01 kt, or a fully *decoupled* nuclear explosion with a yield of about 1 kt. Based on more optimistic assumptions about the conditions to be encountered and prospective improvements in data processing capability, this same network could have a detection capability as low as m_b 2.0. Detection capability contours for one such proposed 30-array internal network are shown in figure 4-7.

Considerations in Choosing Monitoring Thresholds

Depending on the number of internal stations, detection capabilities could either increase or decrease. The point, however, is that very low detection thresholds, down to magnitude 2.0, can be achieved. In fact, almost any desired signal detection level can theoretically be obtained by deploying a sufficient number of internal stations; although there may be disagreements over the number and types of stations needed to achieve a given threshold. The disagreements could be resolved as part of a learning process if the internal network is built up in stages.

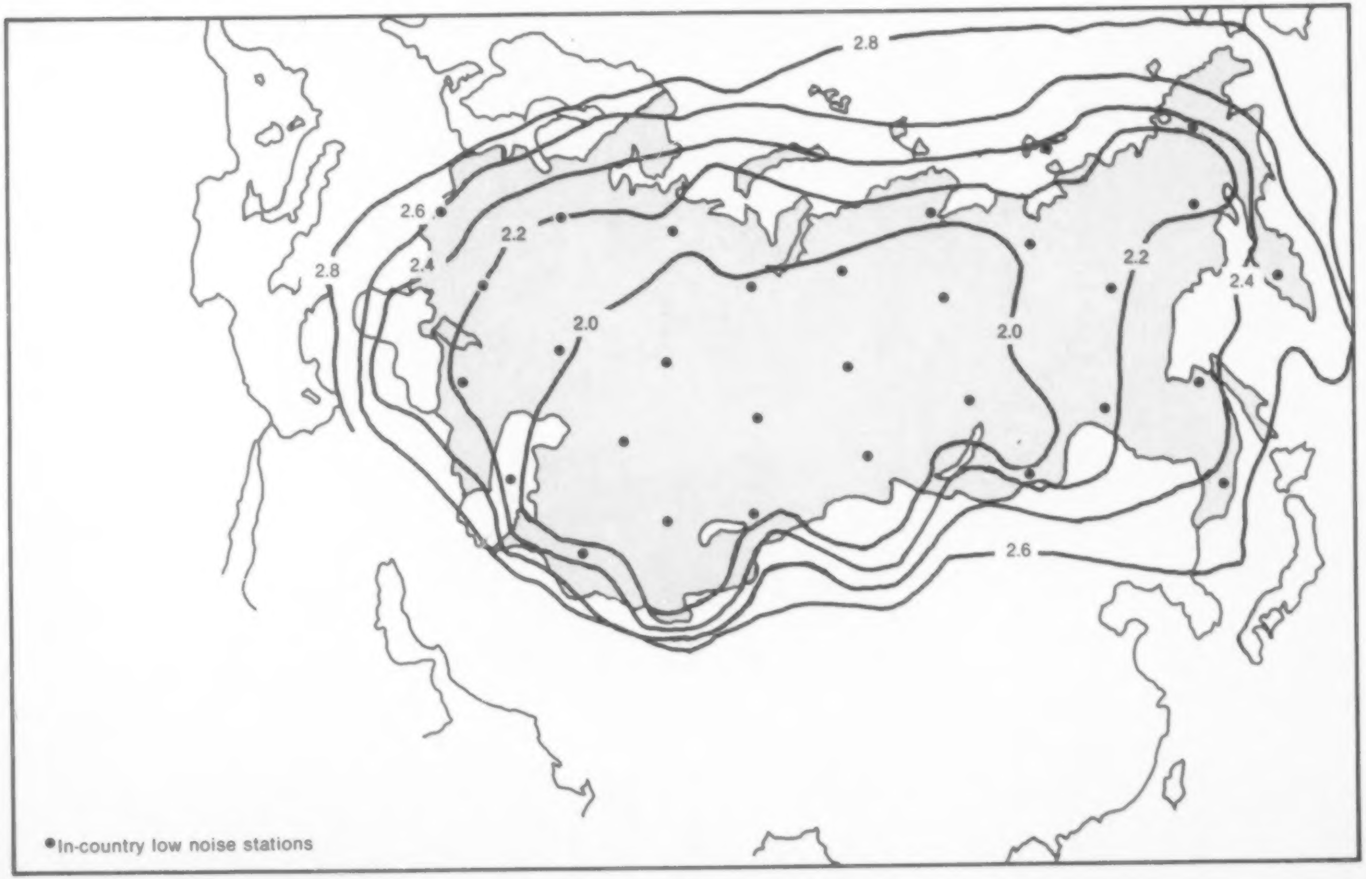
Another consideration is that all detection estimates used in this report are based on a 90-percent probability of four or more stations detecting an event. While this may be a prudent estimation procedure from the monitoring point of view, an evader who did not wish to be caught might adopt a considerably more cautious point of view. (See chapter 2 for a discussion of the relationship between uncertainty and cheating opportunities.) Such concerns might be increased by the realization that for many seismic events, there will be at least one station that will receive the signal from the event with a large signal-to-noise ratio. The signal will be so large with respect to the noise at this station that the validity of the signal will be obvious and will cause a search for other associated signals from neighboring seismic stations. The possible occurrence of such a situation would be of concern to a country contemplating a clandestine test.

Throughout all of this discussion it must be kept in mind that an improvement in detection capability does not necessarily correspond directly to an improvement in our monitoring capability. Although a reduced detection threshold must be accompanied by a reduced identification threshold; occurrences such as industrial explosions might ultimately limit the identification threshold. For example, the estimate of detection capability for internal stations which is given above, m_b 2.0 to 2.5, corresponds to a decoupled explosion of about 1 kt. A decoupled 1 kt explosion produces the same m_b signal as a 1/70 kt (15) ton chemical explosion. At such small magnitude levels, there are hundreds of chemical explosions detonated in any given month in the U.S.S.R. and in the United States.

Use of High-Frequency Data

It has long been known to seismologists that seismic signals of moderate to high frequencies can indeed be detected at large distances from the source under favorable geological conditions. Such is the case in the eastern United States, and it is generally thought that this is also true of most of the Soviet Union. In con-

Figure 4-7.—Example of Calculated Detection Capability


2.8
2.6
2.4
2.2
2.0
2.0
2.2
2.4
2.6
2.8
●In-country low noise stations

Calculated detection capability (in m_b units) of an external network plus 30 internal, low-noise arrays.

SOURCE: Modified from Lawrence Livermore National Laboratory.

trast, tectonic regions such as the western United States and the southern fringe of the U.S.S.R. are generally characterized by stronger attenuation of high frequencies, which are therefore lost beyond relatively short distances.

The design and development of a nuclear monitoring strategy based on high-frequency seismic signals calls for:

- A determination of Earth structure within and around the region to be monitored, and an evaluation of its signal transmission characteristics at high frequencies.
- A methodology for identifying and selecting sites with low ground noise, and equipping such sites with high performance sensors and recording systems, so as to achieve the largest possible signal-to-noise ratio.
- A reliable understanding of the high-frequency radiation of natural (earthquakes) and man-made (explosions) seismic sources. Although empirical evidence based on direct observations is sufficient in principle, a predictive capability, based on theory, is required to assess properly new and untested monitoring conditions.

Such requirements parallel in every respect the usual constraints placed on standard monitoring systems. However, direct experimentation pertinent to high-frequency monitoring has been rather limited so far, and the relevant data available today are neither abundant nor diverse. Consequently, an assessment of whether these requirements can be met relies of necessity on some degree of extrapolation from our present experience, based on theoretical arguments and models. This situation leaves room for debate and even controversy.[2]

Recently, it has been argued that the capability to detect and identify low-yield nuclear explosions could be greatly improved by using high-frequency (30 - 40 Hz) seismic data.[3] The major points of the argument are:

- that natural seismic ground noise levels are very low at high frequencies, and that large seasonal fluctuations are not anticipated;
- that careful station selection could make it possible to emplace seismic sensors in particularly quiet sites; and
- that present seismic recording technology allows high-fidelity recordings by suppression of system-generated noise to levels below ground noise even at high frequencies and at quiet sites.

Advocates of high-frequency monitoring explain the efficiency of high-frequency wave propagation observed in the North American shield in terms of a simple model for attenuation of seismic waves in stable continental regions and argue that the model applies as well to stable continental Eurasia. Finally, they argue that suitable parameterizations of theoretical models of earthquakes and underground explosions provide adequate predictive estimates of the relative production of high-frequency energy by various seismic sources and justify their choice by comparison with limited observations.

Based on these arguments and a systematic modeling procedure, some seismologists reason that the most favorable signal-to-noise ratio for detection of low yield (i.e. small magnitude) events in stable continental areas will be found at moderate to high frequencies (about 30 Hz). They further infer that a well-designed network of 25 internal and 15 external high-quality stations using high frequencies would yield multi-station, high signal-to-noise detection of *fully decoupled* 1-kt explosions from any of the potential decoupling sites within the U.S.S.R., and result in a monitoring capability at the 1-kt level.

On the other hand, the inference that such significant benefits would necessarily accrue by relying on high-frequency recordings has been strongly questioned in the seismological community. Indeed many scientists feel that the case is currently unproven. Major points of disagreement include:

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[2] High quality seismic data is now becoming available from the NRDC-Soviet Academy of Sciences stations in the Soviet Union and the United States, with more widely distributed stations to be added in 1988 in both countries. This data may help reduce the necessity for extrapolation and decrease the uncertainties that foster the debate.

[3] For example, J. F. Evernden, C. B. Archambeau, and E. Cranswick, "An Evaluation of Seismic Decoupling and Underground Nuclear Test Monitoring Using High-Frequency Seismic Data," *Reviews of Geophysics*, vol. 24, No. 2, 1986, pp. 143-215.

- The concern that the theoretical seismic source models used so far in the analysis described above are too simple. Studies aimed at constructing more realistic models indicate that the high-frequency waves generated by seismic sources are strongly affected by complexities of source behavior that the simple models do not take into account. On the other hand, advocates of high frequency seismic monitoring believe that the models they have used have successfully predicted a number of characteristics of seismic sources that were subsequently verified and that none of the many well-documented observations of seismic wave characteristics from large events are in conflict with their theoretical model predictions. Thus they argue that the model predictions, for somewhat smaller events at somewhat higher frequencies than are ordinarily studied, are reasonable extrapolations.
- The concern that it may be difficult to identify candidate station sites where the high-frequency noise is sufficiently low to permit actual realization of the desired benefits. Experience to date is limited, and one does not really know whether a given site is suitable until it has been occupied and studied for at least a year. On the other hand, advocates of high frequency monitoring feel that suitable low-noise sites are not at all rare and can be rather easily found in most, if not all, geologic environments within the continents. They argue that stations selected so far have had adequately low high-frequency noise characteristics and the selection process was neither difficult nor time consuming. They conjecture that doubts are based on misidentification of high-frequency internal seismic recording system noise as ground noise, and that once high-performance systems with low system noise become more wide-spread, this concern will disappear.
- The concern that observations which can be employed to test directly the validity of the proposed use of high frequencies are as yet quite scant, and their interpretation is not free of ambiguities. For example, the characterization of source spectra and the propagation and attenuation of high-frequency waves remain issues which are not resolved unequivocally by observations, and yet are critical to the formulation of a high-frequency monitoring strategy. Similarly, available data often exhibit an optimal signal-to-noise ratio at frequencies near 10 Hz, in apparent disagreement with the arguments enunciated earlier. In response to these concerns, proponents argue that the NRDC-Soviet observations of signal-to-noise ratios greater than 1 and out to frequencies above 20 Hz provides evidence for the potential of high frequency monitoring. While proponents of high frequency monitoring agree that the observations of the largest signal to noise ratios for signals from seismic events often occur near 10 Hz, this is not in disagreement with the predictions or technical arguments advanced for high-frequency monitoring. They argue that these observations are obtained from seismic receivers with system noise that is greater than ground noise at frequencies above 10 Hz, and that many of the observations are from industrial explosions that are ripple-fired and so are expected to have lower high-frequency content than a small nuclear test.
- The concern stated earlier that the motivation for the proposed high-frequency monitoring approach uses contested theoretical arguments and models to extrapolate from our present experience and thus attempt to guide further steps towards a significantly improved capability. In the present case, models are used to extrapolate both toward high frequencies and toward small yields, and just how far one

may extrapolate safely remains a matter of debate. The proponents of high frequency monitoring agree that the data relating to high frequency monitoring is limited with respect to the geologic regions to which it pertains. Furthermore, it is clear that experience in the systematic detection and identification of very small seismic events using high-frequency data is absent and that, as a consequence, it has been necessary to extrapolate from experience with larger seismic events where lower frequency data is used. Proponents believe, however, that what limited data is available does support the most critically important predictions; these being the apparent availability of low-noise sites and the efficiency of high-frequency wave propagation to large distances.

These controversial aspects notwithstanding, **there is general agreement among seismologists that good signal-to-noise ratios persist to higher frequencies than those used routinely today for nuclear monitoring.** In particular, data in the 10 - 20 Hz band show clear signals which are undoubtedly not used optimally. Given the fact that recording of even higher frequencies is demonstrably feasible in some situations, and given the potential advantages for low-yield monitoring, the augmentation of our experience with such data, the concomitant continued development of appropriate analysis techniques to deal with them, and the validation of the models used in their interpretation are goals to be pursued aggressively. Not until a sufficient body of well-documented observations of this nature has been collected can we expect to achieve a broad consensus about the performance of high-frequency monitoring systems.

Arrays v. Three-Component Stations

Both small-aperture, vertical-component arrays such as NORESS, and three-component, single-site stations such as the RSTN station have been considered for use as internal stations. In choosing which to use, it should be realized that many combinations of arrays and single stations will provide the same capability. For example, for any array network, there is a single station network with comparable capability; but the network of single stations probably requires about twice as many sites. Although a single array has advantages over a single three-component station (see chapter 3), for monitoring purposes it is preferable to have a large number of station sites with three-component stations rather than to have a small number of sites with arrays. This is true because it permits better accommodation to details of regional geology, and better protection against noise sources temporarily reducing capability of the network as a whole. However, if the number of sites is limited by negotiated agreement, but the instrumentation can include either arrays or three-component stations, then arrays are preferable. This is true both because of the inherent redundancy of arrays and their somewhat better signal-to-noise enhancement capability over single three-component stations.

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Identifying Seismic Events

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Chapter 5

Identifying Seismic Events

Once a seismic event has been detected, the next step is to determine whether it was created by an underground nuclear explosion.

INTRODUCTION

Once the signals from a seismic event have been detected, and the event located, the next step in seismic monitoring is that of identification. Was the event definitely, or possibly, an underground nuclear explosion, or can the signals be identified unambiguously as having another cause? As discussed in the previous chapter, seismic signals are generated by natural earthquakes and by natural rockbursts in mines, as well as by chemical and nuclear explosions. The identification problem in seismic monitoring, called the *discrimination* problem, is to distinguish underground nuclear explosions from other seismic sources.

In the case of a located seismic event for which signals are large, that is, larger than could be ascribed to a chemical explosion or a rockburst, the only candidates for the source of the signals are an earthquake or a nuclear explosion. Physical differences between earthquakes and nuclear explosions cause their seismic signals to differ, and these differences can be used to identify the events.

Identification becomes more complicated, however, for small events. When identifying small events (comparable in size to an explosion of less than 10 kilotons), the identification procedures encounter four types of difficulty that do not arise for larger events:

1. the quality of available signals is typically lower;
2. the number of natural events that must be discriminated against is larger;
3. the possibilities now include chemical explosions and rockbursts;
4. the event, if nuclear, is of a size where attempts may be made to muffle or hide the seismic signal.

Each of these difficulties becomes more severe at lower yields.

The last difficulty listed above brings up the subject of evasion which is discussed in the next chapter. For the purposes of understanding this chapter, however, the reader should recognize that identification capabilities must always be considered against the feasibility of various evasion scenarios. The successful use of a muffling or decoupling evasion technique could cause a 1-10 kt decoupled nuclear explosion to produce seismic signals comparable to either a chemical explosion of 10-100 *tons* respectively, or an earthquake ranging from magnitude 2-3 respectively. The similarity in size and, in some cases, the properties of the signals for these three types of events pose the most serious monitoring challenges. The monitoring system must be able to demonstrate a capability to identify with high confidence seismic events whose signals might be intentionally reduced or hidden through credible evasion techniques. It is the need to demonstrate such a capability, as signals become smaller, that ultimately sets the threshold for seismic identification.

The present chapter describes the different kinds of seismic sources and the basis for solving the identification problem. It then describes capabilities of current seismic networks, and how these capabilities might be improved by the addition of new seismic stations, including stations within the U.S.S.R.

BASIS FOR SEISMIC IDENTIFICATION

The seismic signals from a nuclear explosion must be distinguished from seismic signals created by other events, particularly earthquakes, chemical explosions, and rockbursts. Most seismic signals from located events are caused by earthquakes, although chemical explosions are also present in large numbers. Significant rockbursts and other sources of seismic signals are rare. A monitoring network, however, will encounter seismic signals created by all of these sources and must be able to identify them. Consequently, the burden on any monitoring network will be to demonstrate a capability to detect and identify with high confidence a clandestine nuclear test against the background of large numbers of earthquakes and industrial explosions and infrequent rockbursts. This section reviews basic properties of these other seismic sources and discusses the physical basis for discriminating them from nuclear explosions.

Earthquakes

Earthquake activity is a global phenomenon, though most of the larger earthquakes are concentrated in active tectonic regions along edges of the Earth's continental and oceanic plates (figure 5-1). In the U.S.S.R., most large earthquakes are located in a few active regions along the southern and eastern borders of the country (figure 5-2). For the many earthquakes occurring along the Kurile Islands region on the Pacific border of the Soviet Union, the shallow earthquakes generally occur on the ocean side of the islands, while the deeper earthquakes occur beneath the islands and toward the U.S.S.R. landmass (figure 5-3). Elsewhere, earthquakes can occur as deep as 700 kilometers in the Earth's mantle.

In figure 5-2, large areas of the U.S.S.R. are shown for which there is no significant earthquake activity. Given presently available information, such areas are referred to as *aseismic*; although some activity may occur in these regions at magnitudes below m_b 3.0.

As table 1 illustrates, there are about 7,500 earthquakes that occur with m_b 4.0 or above each year, and about 7 percent of these occur in the Soviet Union. However, approximately two-thirds of the Soviet seismicity occurs in oceanic areas, mainly off the Kurile-Kamchatka coast. Seismicity in oceanic areas does not raise an identification problem because acoustic sensors provide excellent identification capability for nuclear explosions in water. Consequently, it is earthquakes on Soviet land areas from which nuclear explosions need to be differentiated. For example, at the magnitude level of m_b 4.0 and above, where there are 7,500 earthquakes each year, approximately 183 occur on Soviet land areas and would need to be identified. The number of such earthquakes that occur each year above various magnitudes is shown in the third column of table 1. The smaller the magnitude, the more earthquakes there are.

Earthquakes and their associated seismograms have been studied on a quantitative basis for about 100 years. Since 1959, seismologists have engaged in a substantial research effort to discriminate between earthquakes and explosions by analyzing seismic signals. Thousands of studies have been conducted and reports written. As will be discussed in the following section, this identification problem is now considered to be solved for events above a certain magnitude.

Table 5-1.—Approximate Numbers of Earthquakes Each Year, Above Different Magnitude Levels

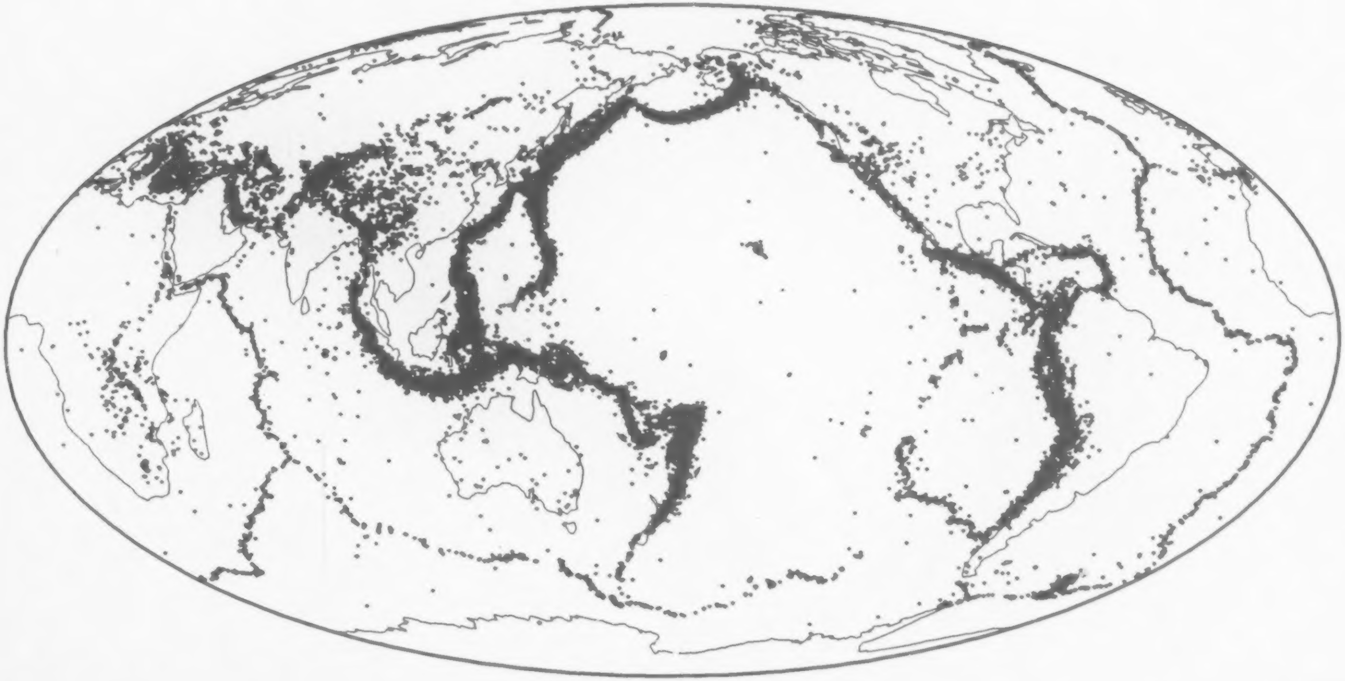
m_b	Globally[a]	Soviet Union[b]	Soviet land areas[c]
5.0	950	70	23
4.5	2,700	200	67
4.0	7,500	550	183
3.5	21,000	1,500	500
3.0	59,000	4,200	1,400
2.5	170,000	12,000	4,000

[a] Based on F. Ringdal's global study of a 10-year period, for which he finds the statistical fit $\log N = 7.47 - 0.9m_b$. F. Ringdal, "Study of Magnitudes, Seismicity, and Earthquake Detectability Using a Global Network," in The Vela Program, Ann U. Kerr, (ed.), Defense Advanced Research Projects Agency, 1985.

[b] Based on 7 percent of global earthquakes with numbers rounded up slightly.

[c] Based on removing two-thirds of Soviet Union earthquakes. Two-thirds of the earthquakes in the Soviet Union occur in oceanic areas, e.g., off the Kurile-Kamchatka coast and, therefore, do not present an identification problem.

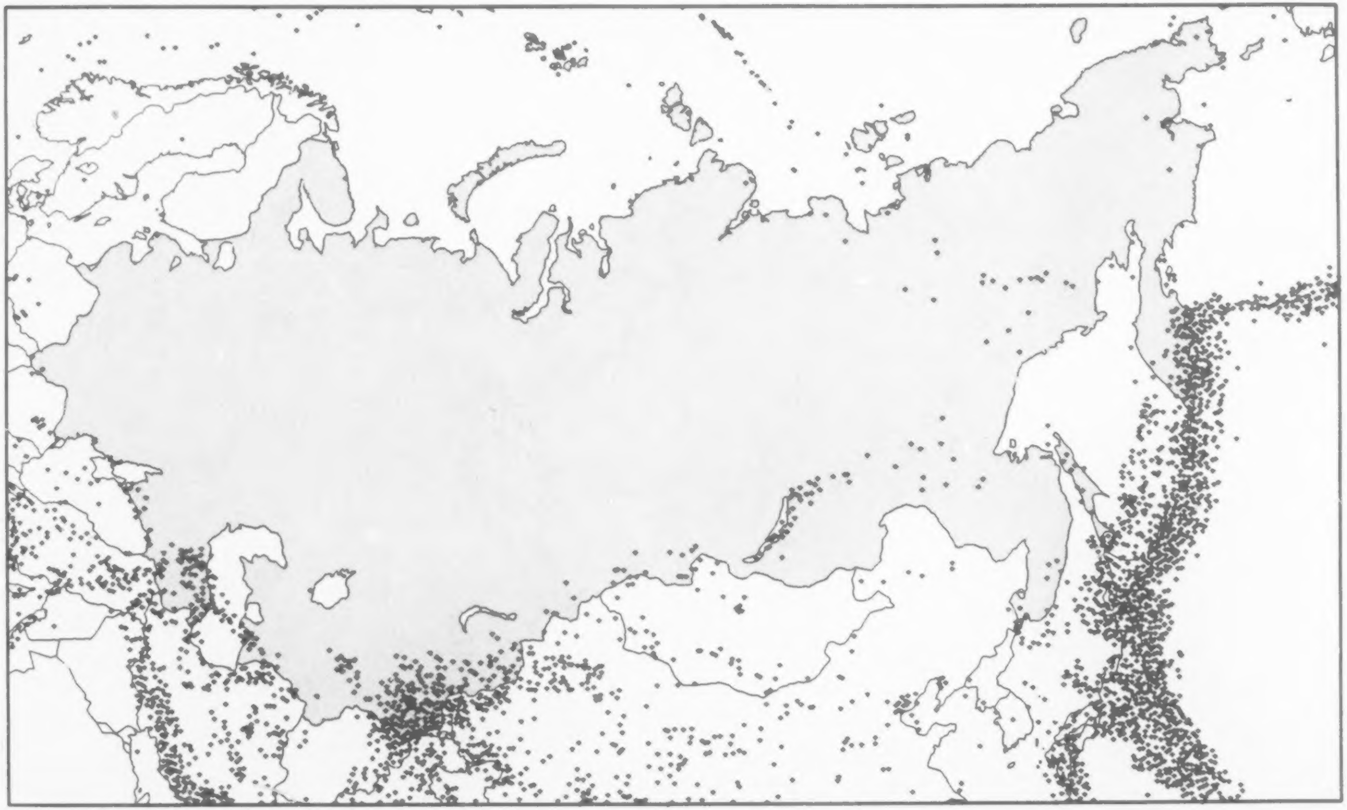
Figure 5-1.—Seismicity of the World, 1971-1986



Distribution of earthquakes with magnitudes ≥ m_b 4.0.

SOURCE: U.S. Geological Survey.

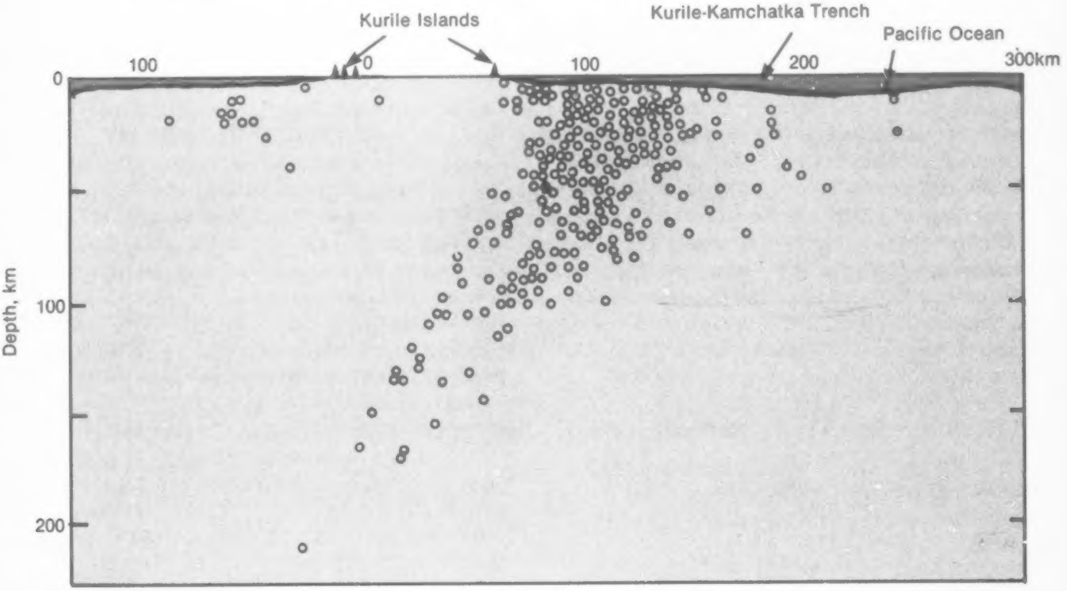
Figure 5-2.—Seismicity of the U.S.S.R. and the Surrounding Areas, 1971-1986



Seismicity for a 15-year period. Many of the earthquakes shown are located outside the U.S.S.R. to the south or in the Pacific Ocean region.

SOURCE: U.S. Geological Survey.

Figure 5-3.—Cross-Sectional View of Seismicity Along the Kurile-Kamchatka Coast



Two-thirds of Soviet seismicity at magnitudes greater than m_b 3.5 is off the Kurile-Kamchatka coast. This sectional view shows that almost all these events are deep, below land or shallow, below ocean. Neither case is a candidate explosion location.

SOURCE. L.R. Sykes, J.F. Evernden, I.L. Cifuentes, American Institute of Physics, *Conference Proceedings 104*, pp. 85-133, 1983.

From these studies, a number of identification methods have evolved. These methods all have as their basis a few fundamental differences between nuclear explosions and earthquakes. These differences are in:

- location,
- geometrical differences between the point source of an explosion and the much larger rupture surface of an earthquake, and
- the relative efficiencies of seismic wave generation at different wavelengths.

With regard to the first difference, many earthquakes occur deeper than 10 km, whereas the deepest underground nuclear explosions to date have been around 2.5 km and routine weapons tests under the 150 kt threshold appear all to be conducted at depths less than 1 km. Almost no holes, for any purpose, have been drilled to more than 10 km deep. The exceptions are few, well known, and of a scale that would be difficult to hide. Because nuclear explosions are restricted to shallow depths (less than 2.5 km), discrimination between many earthquakes and explosions on the basis of depth is possible in principle. In practice, the uncertainty in depth determination makes the division less clear. To compensate for the possibility of very deep emplacement of an explosion, the depth must be determined to be below 15 km with high confidence before the event is to be identified unequivocally as an earthquake. Events with shallower depths that show large uncertainties in depth determination might be considered as unidentified on the basis of depth.

With regard to source geometry, the fundamental differences are due to how the seismic signals are generated (see box 5-A). As discussed in chapter 3, an underground nuclear explosion is a highly concentrated source of compressional seismic waves (P waves), sent out with approximately the same strength in all directions. This type of signal occurs because the explosion forces apply a fairly uniform pressure to the walls of the cavity created by the explosion. The simple model of a nuclear explosion is a spherically symmetric source of P waves only. This contrasts with an earthquake, which is generated as a result of massive rock failure that typically produces a net shearing motion. It is common here to think in terms of two blocks of material (within the crust, for shallow events) on opposite sides of a fault. The stress release of an earthquake is expressed in part by the two blocks moving rapidly (on a time scale of seconds) with respect to each other, sliding in frictional contact over the plane of the fault as a result of the spontaneous process of stress release of rock—stress that has accumulated over time through geologic processes. Because of this shearing motion, an earthquake radiates predominantly transverse motions—i.e., S waves, from all parts of the fault that rupture. Though P waves from an earthquake are generated at about 20 percent of the S-wave level, they have a four-lobed radiation pattern of alternating compressions and rarefactions in the radiated first motions, rather than the relatively uniform pattern of P-wave compressions radiated in all directions from an explosion source. These idealized radiation patterns, P waves from an earthquake and an explosion, are shown schematically at the top of figure 5-4. These two types of source geometries result in the following differences:

1. **Energy partitioning.** The energy of a seismic event is partitioned into compressional, shear, and surface waves. Earthquakes tend to emit more energy in the form of shear waves and surface waves than explosions with comparable compressional waves (figure 5-4). At lower magnitudes, however, differences of this type may be difficult to distinguish if the surface waves from either source become too small to detect.
2. **Dimensions of the source.** Earthquakes tend to have larger source dimensions than explosions because they involve a larger volume of rock. The bigger the source volume, the longer the wavelength of seismic waves set up by the source. As a result, earthquakes usually emit seismic waves with longer wavelengths than explosions. Instead of describing the signal in terms of wavelength, an equivalent description can be given in terms of seismic wave frequency. Explosions, which

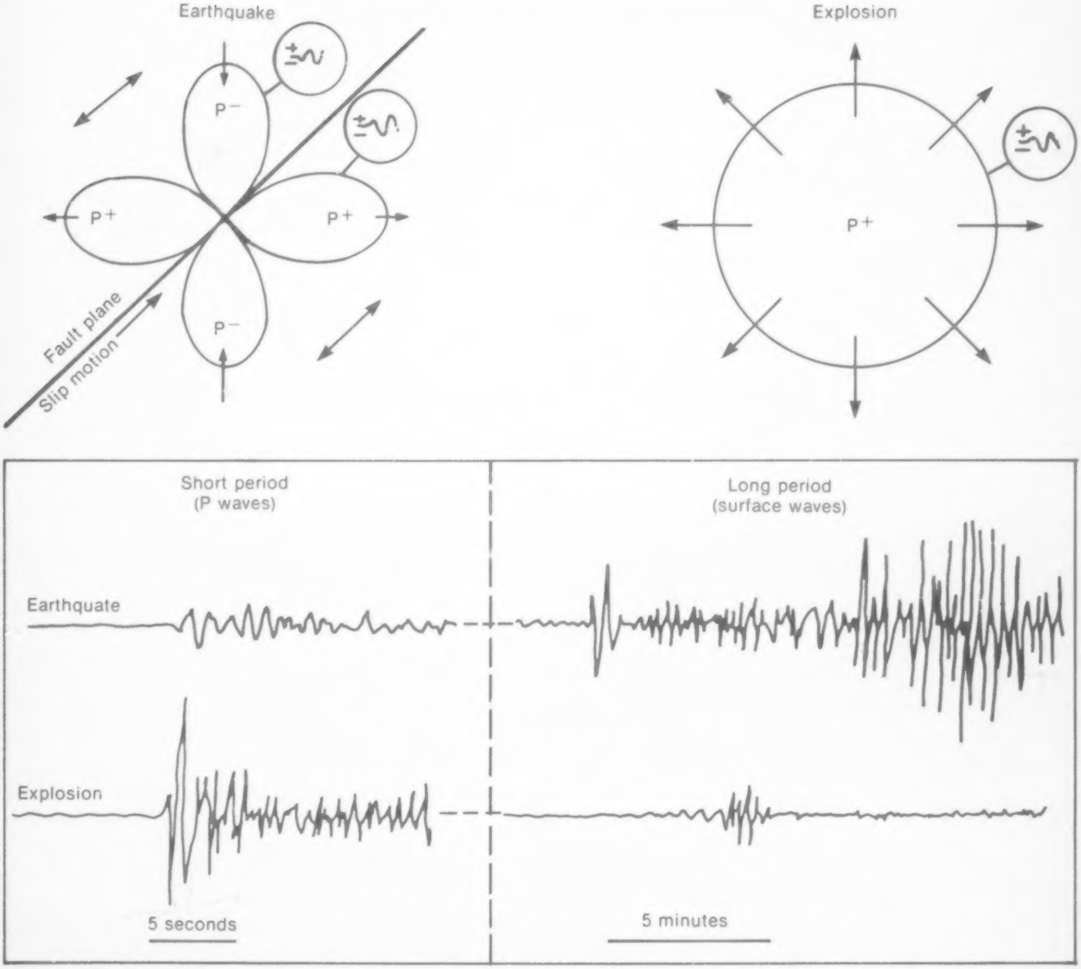
Box 5-A.—Theory and Observation

One of the points on which early efforts at discrimination stumbled was the claim that explosions, because they are concentrated pressure sources, would generate insignificant SH waves and Love waves. (These waves entail types of shearing motion, in which the ground moves in a horizontal direction.) But it was soon found, in the early 1960s, that some explosions generated quite strong SH and Love waves, so this discriminant came to be seen as unreliable.

A salutary further effect was that discriminants based purely on theoretical predictions came to carry little weight until they had passed stringent tests with actual data from explosion and earthquake sources. Occasionally, some useful discriminants are discovered empirically and a theoretical understanding is not immediately available. A recent example of this is the observation that regional phases P_n, P_g, and L_g for small earthquakes in the western U.S. typically exhibit more high-frequency energy (at 6-8 Hz) than do small NTS nuclear explosions of comparable seismic magnitude.* However, in the symbiotic relation between theory and observation, there is generally a framework of understanding in which progress in one field guides workers to new results in the other.

*J.R. Murphy and T.J. Bennett, "A Discrimination Analysis of Short-Period Regional Seismic Data Recorded at Tonto Forest Observatory," *Bulletin of the Seismological Society of America*, vol. 72, No. 4, August 1982, pp. 1351-1366.

Figure 5-4.—Earthquakes v. Explosions


Earthquake
±
±
P−
P+
P+
P−
Fault plane
Slip motion
Explosion
±
P+
Short period
(P waves)
Long period
(surface waves)
Earthquate
Explosion
5 seconds
5 minutes

(Upper) Different radiation patterns for earthquakes and explosions. Earthquakes involve shear motion along a fault plane. Explosions are compressional sources of energy and radiate P waves in all directions.
(Lower) Recorded signals (i.e., seismograms) of earthquakes and explosions generally have different characteristic features. Note the much stronger P-wave:surface-wave ratio, for explosions as compared to the earthquake.

SOURCE: F. Ringdal, "Seismological Verification of Comprehensive Test Ban Treaty," paper presented in "Workshop on Seismological Verification of a Comprehensive Test Ban Treaty," June 4-7, 1985, Oslo, Norway.

are small, intense sources, send out stronger signals at high frequencies; and earthquakes generally have more low-frequency (long-wavelength) energy than explosions (figure 5-4). However, exceptions have been observed and the distinction may diminish for small events. The difference in frequency content of the respective signals, particularly at high frequencies, is a topic of active research.

These basic differences in seismic signal are understood on theoretical grounds; and this theoretical framework guides the search for new empirical methods of identification. As new types of seismic data become available (for example, data from within the Soviet Union), it may be expected that methods of identification will be found that work at smaller magnitude levels. At low magnitudes, however, we have not only the problem of distinguishing nuclear explosions from earthquakes, but also of distinguishing nuclear explosions from the large chemical explosions that are commonly used for industrial purposes such as mining. This is a much more difficult problem because in theory the two source types should produce similar signals.

Chemical Explosions

Chemical explosions are used routinely in the mining and construction industries, and they occur also in military programs and on nuclear test sites. In general, from the seismic monitoring perspective, a chemical explosion is a small spherical source of energy very similar to a nuclear explosion. The magnitudes caused by chemical explosions are generally below m_b 4.0, although events with magnitudes up to m_b 4.5 occasionally occur. The fact that large numbers of chemical explosions in the yield range from 0.001 to 0.01 kt are detected and located seismically is a testament to the capability of local and regional seismic networks to work with signals below m_b 3.0.

There is little summary information available on the number and location of chemical explosions in the U.S.S.R., though it appears that useful summaries could be prepared from currently available seismic data. In the United States, chemical explosions around 0.2 kt are common at about 20 mines. At each of these special locations, tens of such explosions may occur each year. Presuming that similar operations are mounted in the U.S.S.R., this activity is clearly a challenge when monitoring nuclear explosions with yields below about 1 kt. It is also a challenge when considering the possibility that a nuclear testing nation may seek to muffle a larger nuclear explosion (say, around 5 kt), so that its seismic signals resemble those of a much smaller (say, around 0.1 kt) chemical explosion.

The problem of identifying industrial explosions can be partially constrained in three ways:

1. In the United States, almost all chemical explosions detonated with yields 0.1 kt or greater for industrial purposes are in fact a series of more than a hundred small explosions spaced a few meters apart and fired at shallow depth with small time delays between individual detonations. One effect of such "ripple-firing" is to generate seismic signals rather like that of a small earthquake, in that both these types of sources (ripple-fired chemical explosions, and small earthquakes) occur over a large area and thus lose some of the characteristics of a highly concentrated source such as a nuclear explosion. If individual salvos are large enough, however, they might be able to mask the signals from a sub-kiloton nuclear explosion. Recent research on this problem has shown the importance of acquiring seismic data at high frequencies (30-50 Hz); and indeed, such data suggest the existence of a distinctive signature for ripple-fired explosions.[1] [2] [3]
2. Many of the rare chemical explosions above about 0.5 kt that are not ripple fired can be expected to result in substantial ground deformation (e.g., cratering).[4] Such surface effects, together with absence of a radiochemical signal, would indicate a chemical rather than a nuclear explosion source. The basis for this discriminant is

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[1] A.T. Smith and R.D. Grose, "High-Frequency Observations of Signals and Noise Near RSON: Implications for Discrimination of Ripple-fired Mining Blasts," LLNL UCID-20945, 1987.

[2] A.T. Smith, "Seismic Site Selection at High Frequencies: A Case Study," LLNL UCID-21047, 1987.

[3] D.R. Baumgardt, "Spectral Evidence for Source Differences between Earthquakes and Mining Explosions in Norway," *Seismological Research Letters*, vol. 38, January-March 1987, p. 17.

[4] It is also relevant that chemical explosions in the 0.1 - 0.5 kt range are commonly observed to be quite efficient in generating seismic waves. For example, 0.5 kt chemical explosions are known to have m_b around 4.5 for shield regions.

that chemical explosions are typically very shallow.

3. To the extent that remote methods of monitoring chemical explosions are deemed inadequate (for example, in a low yield threshold or comprehensive test ban regime), solutions could be sought by requiring such constraints as prior announcement of certain types of chemical explosions, inspections, shot-time monitoring, and in-country radiochemical monitoring. Note that in the United States (and so perhaps also in the U.S.S.R.) chemical explosions above 0.1 kt occur routinely at only a limited number of sites.

Rockbursts

In underground mining involving tunneling activities, the rock face in the deeper tunnels may occasionally rupture suddenly into the tunnel. This is referred to as a rockburst and results from the difference between the low pressure existing within the tunnel and the great pressure that exists within the surrounding rock. To prevent such mine rockbursts, bracing structures are used in the deeper tunnels.

In terms of magnitude, rockbursts are all small. They occur over very restricted regions of the Earth and generally have a seismic magnitude of less than 4.0 m_b.

The source mechanisms of rockbursts are very similar to those of small earthquakes. In particular, the direction of the first seismic motion from a rockburst will have a pattern similar to that for earthquakes. Therefore, for the seismic identification problem, rockbursts can be considered small earthquakes which occur at very shallow depths.

METHODS OF IDENTIFICATION

Over the years, a number of identification methods have been shown to be fairly robust. Some of these methods perform the identification process by identifying certain earthquakes as being earthquakes (but not identifying explosions as being explosions). Other identification methods identify certain earthquakes as being earthquakes and certain explosions as being explosions. **The identification process is therefore a winnowing process.**

Location

The principal identification method is based on the location of a detected seismic source. If the epicenter (the point on the Earth's surface above the location) is determined to be in an oceanic area, but no hydroacoustic signals were recorded, then the event is identified as an earthquake. Large numbers of seismic events can routinely be identified in this way, because so much of the Earth's seismic activity occurs beneath the ocean. If the location is determined to be land, then in certain cases the event can still be identified as an earthquake on the basis of location alone, e.g. if the site is clearly not suitable for nuclear explosions (such as near population centers) or if there is no evidence of human activity in the area.

Depth

With the exception of epicenter locations, seismic source depth is the most useful discriminant for identifying large numbers of earthquakes. A seismic event can be identified with high confidence as an earthquake if its depth is determined to be below 15 kilometers.

The procedure for determining source depth is part of finding the event location using the arrival time of four or more P-wave signals. Also, certain seismic signals, caused by energy that has traveled upward from the source, reflected off the Earth's surface above the source region, and then traveled down into the Earth, are similar to the P wave out to great distances. A depth estimate can be obtained by measuring the time-difference between the first arriving P-wave energy and the arrival time of these reflected signals. The analysis of broadband data through wave-form modeling is particularly useful for detecting these reflected signals. Empirical methods can also be used, based on comparison with previously interpreted seismic events in the same general region as the event under study.

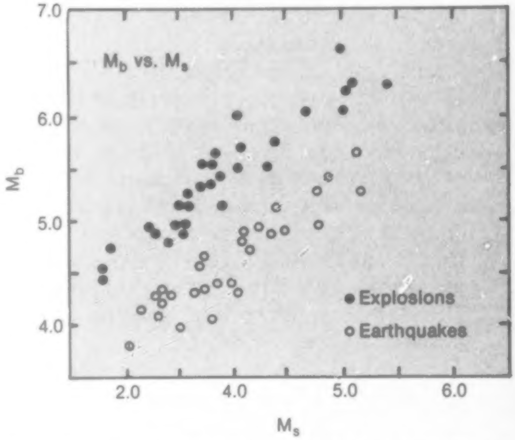
In principle, an advantage of depth as an identification method is that it is not dependent on magnitude: it will work for small events as well as large ones, provided the basic data are of adequate signal quality and the signals are detected at a sufficient number of stations. It will not alone, however, distinguish between chemical and nuclear explosions unless the nuclear explosion is relatively large and deep; or between underground nuclear explosions and earthquakes unless the earthquakes are sufficiently deep.

M_s:m_b

Underground nuclear explosions generate signals which tend to have surface wave magnitude (M_s) and body wave magnitudes (m_b) that differ from those of earthquake signals. This is basically a result of explosions emitting more energy in the form of body waves (high-frequency seismic radiation), and earthquakes emitting more energy in the form of surface waves (low frequency seismic radiation). The phenomenon is often apparent in the original seismograms (figure 5-4), and examples are shown in terms of M_s:m_b diagrams in figures 5-5, 5-6, and 5-7. These diagrams can be thought of as separating the population of explosions from that of earthquakes. For any event which is clearly in one population or another, the event is identified. For any event which is between the two populations (as occasionally happens for explosions at the Nevada Test Site), this method does not provide reliable identification. The method, therefore, has the potential of identifying certain earthquakes as being earthquakes and certain explosions as being explosions.

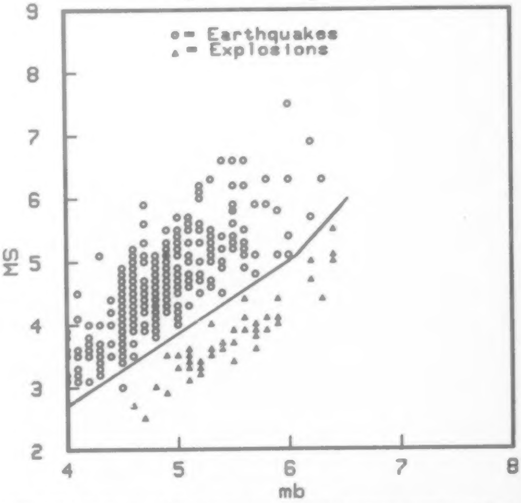
To use this identification method, both m_b and M_s values are required for the event. This is no problem for the larger events, but for smaller events (below m_b 4.5) it can be very difficult to detect low-frequency surface waves using external stations alone.[5] This difficulty is present particularly for explosions, with the

Figure 5-5.—M_s v. m_b for a Suite of Earthquakes and Explosions



SOURCE: P.D. Marshall and P.W. Basham, Geophysical Journal of the Royal Astronomical Society, vol. 28, pp. 431-458, 1972.

Figure 5-6.—M_s v. m_b



SOURCE: L.R. Sykes, J.F. Evernden, I.L. Cifuentes, American Institute of Physics, *Conference Proceeding 104*, pp. 85-133, 1983. [All of the events (both earthquakes and explosions) were corrected for bias.]

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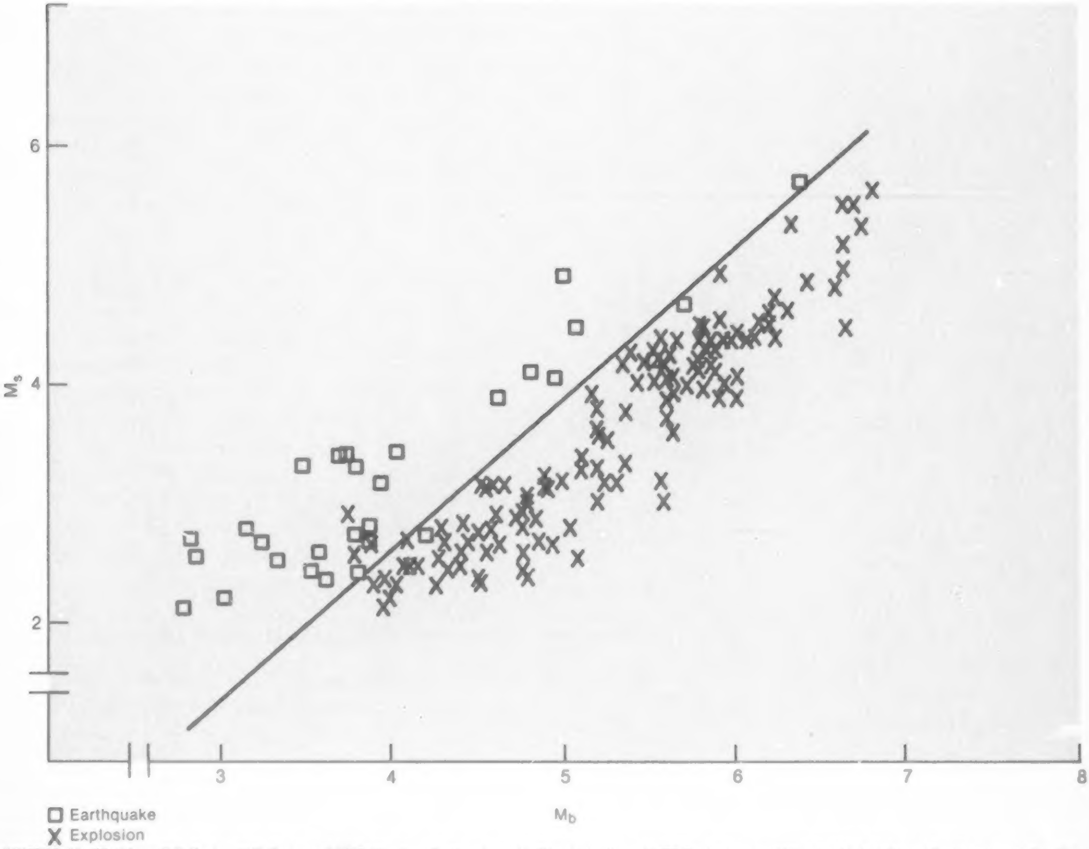
[5] In special studies of regional data that evaluate the M_s:m_b discriminant, it has been found that between 10 percent and 20 percent of the surface waves of small events are masked by signals caused by other events. This, however, has little net effect on the discrimination of events for which more than one station is close enough to receive surface waves.

Figure 5-7.—The m_b:M_s Discriminant for Populations of NTS Explosions and Western U.S. Earthquakes



SOURCE: Modified from S.R. Taylor, M.D. Denny, and E.S. Vergino, *Regional m_b: M_s Discrimination of NTS Explosions and Western United States Earthquakes: A Progress Report*, Lawrence Livermore National Laboratory, January 1986.

result that the M_s:m_b method works intrinsically better for identifying small earthquakes than it does for identifying small explosions. Internal stations would provide important additional capability for obtaining M_s values for events down to m_b 3.0 and perhaps below.

It is known that M_s:m_b diagrams, with their separate populations as shown in figures 5-5, 5-6, and 5-7, tend in detail to exhibit somewhat different properties for sources occurring in different geophysical provinces. That is, the best identification capabilities are obtained, for a particular event of interest, if there is already a data base and an associated M_s:m_b diagram tailored for the general region of the Earth in which that event occurred.

The M_s:m_b method has proven to be the most robust identification technique available for shallow events. For events below m_b 4.0, the separation between the two M_s:m_b populations has been found to decrease in some studies. In the opinion of many seismologists, however, a useful separation (at low magnitudes) may be possible if good quality data for such small events can be found. Again, in the context of monitoring for small underground explosions in the U.S.S.R., obtaining such data would require in-country stations and empirical confirmation.

Other Simple Methods

Several other methods, with applications in particular circumstances, are used to provide identification. Several are still in the research stage, and are having an impact on the design of new instruments and the development of new procedures in data analysis. Some of these methods, based on the whole spectrum of frequencies contained in a seismic signal, are described in the following section. Other methods have been used for decades, and are still occasionally important for use in identifying certain problem events. In order of decreasing importance, the remaining three simple methods can be listed as follows:

1. **The use of "first motion."** By this term is meant an identification method based on differences in the direction of the initial motion of P waves. As illustrated in figure 5-4, an explosion is expected to create initial compressive motions in all directions away from the source, whereas an earthquake typically creates initial compressive motions in some directions and rarefactional motions in others. In a compressive wave, the ground first moves away from the source. In a rarefaction, the ground first moves toward the source. From a good seismometer recording, it is often possible to observe the direction of this initial motion (for example, from observation of whether the ground first moves up or down at the seismometer). This identification method can be powerful if the signal-to-noise ratio is large. But for small events in the presence of seismic noise (as discussed in chapter 4) it can be difficult or impossible to determine the direction of the first motion. Because it is never clear that rarefactional motions may not exist in directions for which network coverage is poor, the method at best identifies an earthquake as an earthquake, but cannot unequivocally identify an explosion as an explosion.
2. **The observation of S waves.** Because of the compressive nature of explosion sources, explosions typically generate less shear wave energy than do most earthquakes. Therefore, the observation of significant shear wave energy is indicative that the event is probably an earthquake.
3. **Complexity.** Many explosion-generated body wave signals tend to be relatively simple, consisting of just a few cycles. Many earthquake-generated body wave signals tend to be relatively complex, consisting of a long series (known as the coda) following the initial few P-wave cycles. The concept of complexity was developed in an attempt to quantify this difference in signal duration. Complexity is the comparison of amplitudes of the initial part of the short-period signal with those of the succeeding coda. There are cases, however, where an explosion signal is complex at some stations and an earthquake signal is simple. Therefore, the complexity method is regarded as not as reliable as M_s:m_b. In practice, whenever the complexity method works, other identification methods also work very well.

Spectral Methods

The basis of the success of M_s:m_b diagrams is, in part, the fact that the ratio of low frequency waves to high frequency waves is typically different for earthquakes and explosions. Thus, M_s is a measure of signal strength at around a frequency of 0.05 Hz, and m_b is a measure of signal strength at around a frequency of 1 Hz. As a way of exploiting such differences, M_s:m_b diagrams are quite crude compared to methods that use a more complete characterization of the frequency content of seismic signals. The analysis of earthquake and explosion signals across their entire spectrum of frequencies is an important component of the current research and development effort in seismic monitoring.

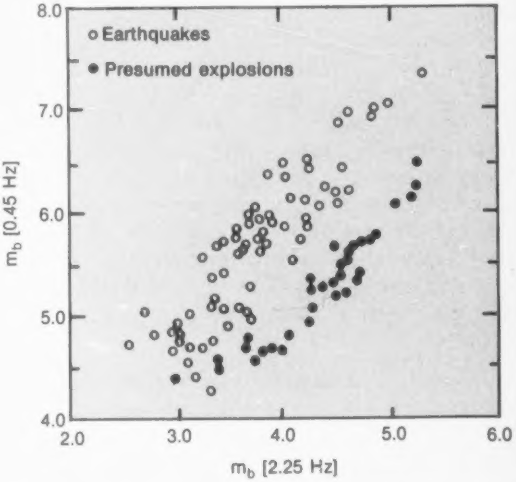
Because M_s:m_b diagrams work well when surface waves are large enough to be measured, the main contribution required of more sophisticated analysis is to make better use of the information contained in the P-wave signals and other large amplitude, high frequency signals. This offers the prospect of improved identification capabilities just where they are most needed, namely for smaller events. Thus, instead of boiling down the P-wave signals at all stations simply to a network m_b value, one can measure the amplitude at a variety of frequencies and seek a discriminant which works on systematic differences in the way earthquake and explosion signals vary with frequency. One such procedure is the *variable frequency-magnitude (VFM)* method, in which the short-period body wave signal strength is measured from seismograms filtered to pass energy at different frequencies, say, f_1 and f_2.[6] Discrimination based on a comparison of $m_b(f_1)$ and $m_b(f_2)$ in many cases shows a clear separation of earthquake and explosion populations (figure 5-8).[7,8,9]

An analogy for the VFM discriminant would be a person's ability to tell by ear the difference between a choir with loud sopranos and weak contraltos, and a choir with loud contraltos and weak sopranos. M_s:m_b is like comparing basses and contraltos. For small events, VFM is complementary to M_s:m_b in several ways: VFM is improved by interference of the main P wave with waves reflected from the surface above the explosion, while M_s:m_b is degraded; VFM is more effective for hard rock explosions, while M_s:m_b will preferentially discriminate explosions in low-velocity materials; and VFM is insensitive to fault orientation. Further, the M_s:m_b method requires averaging over observations from a network of stations surrounding the event, while the VFM method may be applied at a single station at any distance and direction from the source. It is found in practice, however, that the VFM method is most reliable when several high performance stations are used. (Obviously if several stations provide VFM data independently identifying an event, as an explosion for example, then assigning a numerical probability that the event observed was indeed an explosion can be accomplished with more reliability and confidence.) VFM is more sensitive to noise and regional attenuation differences than M_s:m_b, but *the main point is that simultaneous use of both methods should allow improved discrimination of small events.*

High-Frequency Signals

The use of high-frequency signals in seismic monitoring is strongly linked to the question of what can be learned from seismic stations in the U.S.S.R. whose data is made available to the United States. Such "in-country" or "internal" stations were considered in CTBT negotiations in the late 1950s and early 1960s, and the technical community concerned with monitoring in those years was well aware that seismic signals up to several tens of Hz could propagate from explosions out to distances of

Figure 5-8.—The VFM Method



The body-wave magnitude is determined at two different frequencies. Earthquakes and explosions fall into separate populations because explosions are relatively efficient at generating higher frequencies.

SOURCE: J.L. Stevens and S.M. Day, *Journal of Geophysical Research*, vol. 90, pp. 3009-3020, 1985.

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[6] C.B. Archambeau, D.G. Harkrider and D.V. Helmberger, U.S. Arms Control Agency Report, "Study of Multiple Seismic Events," California Institute of Technology, ACDA/ST-220, 1974.

[7] J.F. Evernden, "Spectral Characteristics of the P-codas of Eurasian Earthquakes and Explosions," *Bulletin of the Seismological Society of America*, vol. 67, 1977, pp. 1153-1171.

[8] J.M. Savino, C.B. Archambeau, and J.F. Masso, *Discrimination Results From a Ten Station Network*, DARPA Report SSS-CR-79-4566, S-CUBED, La Jolla, CA, 1980.

[9] J.L. Stevens and S.M. Day, "The Physical Basis for m_b:M_s and Variable Frequency Magnitude Methods for Earthquake/Explosion Discrimination," *Journal of Geophysical Research*, vol. 90, March 1985, pp. 3009-3020.

several hundred kilometers. The seismic waves most prominent at these so-called "regional distances" (by convention, this means distances less than about 2,000 km) are known as P_g, P_n, S_n, and L_g (see ch. 3 for a discussion of these regional waves). P_g propagates wholly within the crust; P_n and S_n travel at the top of the mantle just below the base of the crust; and L_g, guided largely by the crustal layer, is often the strongest signal and is sometimes observed across continents even at distances of several thousand kilometers.

However, this early interest in regional waves lessened once the Limited Test Ban Treaty of 1963 was signed and it was recognized that subsequent programs of large underground nuclear explosions could be monitored teleseismically (i.e., at distances beyond 2,000 km), so that internal stations were not needed. At teleseismic distances, seismic body wave signals are usually simpler and have indeed proved adequate for most purposes of current seismic monitoring, even under treaty restrictions on underground nuclear testing that have developed since 1963. Thus, it is in the context of considering further restraints on testing, such as a comprehensive or low-yield test ban, that the seismic monitoring community needs to evaluate high-frequency regional seismic signals. The basis for the role of high-frequency monitoring, in such a hypothetical new testing regime, is that the greatest challenge will come from decoupled nuclear explosions of a few kilotons, and for them the most favorable signal-to-noise ratios may be at high frequency. Internal stations, of high quality and at quiet sites, will be essential to address the monitoring issues associated with such events.

It is clear that a dedicated program to make optimal use of high-frequency seismic data from internal stations should lead to significant improvements in detection capability.[10] The daily recording of many very small seismic events, together with the possibilities for evasion at low-yields, focuses attention on the discrimination problem for events in the magnitude range m_b 2.0 to m_b 4.0.

For an explosion that is well-coupled to the ground, an $m_b = 2.0$ can be caused by only a few thousandths of a kiloton, that is, a few tons of TNT equivalent. At this level, a monitoring program would confront perhaps 1,000 to 10,000 chemical explosions per year. Given the difficulty of discriminating between chemical and nuclear explosions, it is clear that below some level events will still be detected but identification will not be possible with high confidence. However, recognizing that relatively few chemical explosions occur at the upper end of this m_b range (2.0 - 4.0), where many chemical explosions can be identified by characteristics of their signals over a broad frequency band (see the earlier discussion of ripple-fired chemical explosions), high frequency data recorded within the U.S.S.R. can clearly contribute substantially to an improved monitoring capability. It is difficult to reach precise but general conclusions on what future yield levels could be monitored, because much will depend on the degree of effort put into new seismic networks and data analysis. Conclusions would depend too on judgments about the level of effort that might be put into clandestine nuclear testing. The discussion of evasion scenarios is taken up in the next chapter, and high-frequency seismic data are clearly useful for defeating some attempts to hide small nuclear explosions.

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[10] For a more complete discussion of the use of high-frequency data for detection, see ch. 4, "Detecting Seismic Events."

IDENTIFICATION CAPABILITY

By applying one or more of the methods discussed above, many seismic events can be identified with high confidence. Note, however, that no one method is completely reliable. It is the set of different identification methods, taken as a whole and applied in a systematic fashion, that must be assessed when giving summaries on capability.

Identification Capability Within the U.S.S.R. Using No Internal Stations

The *identification* capability of any network of seismic stations will always be poorer than the *detection* capability for that network. In general, a rough estimate of the 90 percent identification threshold will be about 0.5 m_b above the 90 percent detection threshold for magnitudes above m_b 3.5. Below a magnitude of about 3.5 m_b, this difference may be larger than 0.5 m_b.

In the previous chapter, a network consisting of a dozen or so arrays all *outside* the Soviet Union was discussed as a type example to convey a sense of what capabilities can be achieved. A cautious calculation of the *detection* capability for such a network was that it would have a 90 percent probability of detecting at four or more stations all seismic events within the Soviet Union with a magnitude (m_b) of 3.5 or greater.[11] Therefore, for seismic events in the U.S.S.R., a cautious estimate of the *identification* capability of such a network external to the Soviet Union is that the 90 identification threshold will be m_b 4.0. From table 5-1, it can be seen that approximately 180 earthquakes occur at magnitude 4.0 or above each year on Soviet land areas. This would mean that approximately 18 of these earthquakes would not be identified with high confidence by routine seismic means alone. This, however, does not translate into an opportunity to cheat, because from the cheater's perspective there is only a one-in-ten chance that any given event above this magnitude will not be identified through seismic means.

Events larger than this will be identified seismically with even higher confidence. A larger percentage of the events that are smaller will not be identified, and the number of events will also increase with decreasing seismic magnitude.

Identification Capability Within the U.S.S.R. Using Internal Stations

With a number of internal stations, it is clearly possible to attain a much improved detection and location capability within the Soviet Union. From estimates described in the previous chapter, there is consensus that detection capability (90 percent probability of detection at four or more stations) of m_b 2.0 - 2.5 can be realized, although the debate is not yet resolved on the number of internal stations that would be required, nor on whether the value is closer to m_b 2.0 or m_b 2.5.

A detection capability down to somewhere in the range m_b 2.0 - 2.5, however, cannot be easily translated into a statement about identification capability. Estimation of the capability of hypothetical networks, using regional seismic waves, is difficult because data on noise levels and signal propagation efficiency are not usually available and assumptions must be made that turn out to have a strong influence on conclusions. Although there is now general agreement on the *detection* capability of hypothetical networks, there are some significant differences in opinion on the identification capability such networks provide.

Discussion of identification capability for small events (m_b in the range 2.5 - 4.0), using internal stations, is one of the main areas of technical debate in seismic monitoring. Internal stations will significantly improve the capability to identify many small earthquakes as earthquakes, because such stations extend the discriminants related to the M_s:m_b method down to lower magnitudes. (Internal stations will also permit more accurate determination of epicenters and source depths, thus supplying for small events the most basic information upon which most sources are identified.) But certain types of shallow earthquakes, below some observable magnitude level, are recognized as difficult if not impossible to identify. Also, preliminary use of high frequencies in the United States, to discriminate the explosion signals of small nuclear tests in Nevada from signals of small earthquakes in the western United States, has had some discouraging results. While some say that this is indicative merely of difficulties associated with high frequency seismic wave propagation in the western United States (and that high frequencies propagate with higher signal-to-noise ratios in the U.S.S.R.) or that the instrumentation used in the study prevented data of sufficiently high quality from being brought to bear on the problem, others claim that these preliminary results are valid and are indicative of a fundamental lack of capability in the seismic method, at very small magnitudes.

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[11] See ch. 4, "Detecting Seismic Events."

In the absence of access to extensive Soviet data (particularly, explosion data), some guidance in what might be possible is given by detailed studies of experience with U.S. explosions. Here, it is recognized that use of more than one discriminant results in improvement over use of the single best discriminant (which is usually M_s:m_b). In one multi-discriminant experiment for U.S. explosions and earthquakes which drew heavily on data such as that presented in the last diagram of figure 5-5 (in which m_b for some earthquakes is less than 3.0), seismic discrimination was achieved for all events that had both m_b and M_s values.[12] [13] The discriminants tested were M_s:m_b, combined with a list that included relative excitation of short-period SH waves; relative signal amplitudes for P_n, P_g, L_g, and the largest part of the P wave; generation of higher mode surface waves; long-period surface wave energy density; relative amplitudes of crustal Love and Rayleigh waves; excitation of S_n; spectral ratios of P_n, P_g and L_g; various other spectral methods; and a depth discriminant (see box 5-B). Not included, was what in practice in the U.S.S.R. would be a key but not definitive discriminant, namely an interpretation of the epicenter location.

Box 5-B.—Progress in Seismic Monitoring

Progress in seismic monitoring has been characterized by research results that, when first offered, seemed optimistic but which in several key areas have withstood detailed subsequent study and thus have become accepted. Occasionally there have been setbacks, as noted elsewhere in describing explosion-induced S-waves, and signal complexity.

The current situation is still one of active research, in that spectral discriminants have been proposed that (if corroborated by empirical data, which is now lacking) would permit monitoring down to fractions of a kiloton. A key problem in estimating what future capability is possible is that current research suggestions often entail data analysis significantly more sophisticated than that required for conventional discriminants. Database management would also have to be improved. The requirement, for operational purposes, that a discriminant be simple to apply, is thus in conflict with the requirement that the maximum amount of information be extracted from seismic signals.

From this body of experience, there appears to be agreement that, with internal stations that detect down to m_b 2.0 - 2.5, identification can be accomplished in the U.S.S.R. down to *at least* as low as m_b 3.5. This cautious identification threshold is currently set by the uncertainty associated with identifying routine chemical explosions that occur below this level. Many experts claim that this identification threshold is too cautious and that with an internal network, identification could be done with high confidence down to m_b 3.0. At present, however, this has not been accepted as a consensus view, partly because some experts are on principle unwilling to extrapolate from experience with limited U.S. data to a hypothetical situation that relies on internal stations in the U.S.S.R. On the other hand, advocates of high-frequency monitoring maintain that identification can be routine at thresholds well below m_b 3.0. The acceptance of an identification capability below m_b 3.0, however, would probably require practical experience with data from a monitoring network throughout the Soviet Union.

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[12] M.D. Denny, S.R. Taylor, and E.S. Vergino, "Investigations of m_b and M_s Formulas for the Western U.S. and Their Impact on the m_b:M_s Discriminant," UCRL-95103 LLNL, August 1986.

[13] R.E. Glaser, S.R. Taylor, M.D. Denny, et.al., "Regional Discriminants of NTS Explosions and Western U.S. Earthquakes: Multivariate Discriminants," UCID-20930 LLNL, November 1986.

Chapter 6

Methods of Evading a Monitoring Network

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Chapter 6

Methods of Evading a Monitoring Network

Seismic monitoring when combined with treaty constraints and other monitoring methods must demonstrate a capability to defeat any plausible scenario for evading the monitoring network

INTRODUCTION

The previous chapters have discussed the capability of various networks to detect and identify seismic events. From this discussion it is clear that well-coupled nuclear explosions within the Soviet Union could be detected and identified with high confidence down to yields well-below 1 kiloton using a high-quality seismic network. Yet, in deciding what limits on underground nuclear testing could be verified, further considerations are necessary. A country attempting to conduct a clandestine test would presumably use every practical means to evade the monitoring network by reducing, masking, and disguising the seismic signal created by the explosion. Consequently, detection and identification thresholds cannot be directly translated into monitoring capabilities without considering the various possibilities for evasion.

As we will see in this chapter, certain evasion scenarios could create serious problems for a seismic monitoring system under certain conditions. The need to demonstrate that these evasion scenarios can be defeated (i.e., the explosions in question identified) with high confidence is what limits our monitoring capability. The problem of evasion must be dealt with by a combination of seismic methods, treaty constraints, and other monitoring methods that reduce the difficulties and uncertainties of applying seismic monitoring methods to every conceivable test situation. In short, seismic monitoring needs some help and the obvious approach is to require the structuring of any treaty or agreement to create a testing environment that makes it much more likely that a combination of prohibitions, inspections, and seismic methods will provide the desired high levels of verification capability.

EVASION SCHEMES

Over the past three decades, researchers have conceived a number of theoretical scenarios by which a low-threshold test ban treaty might be evaded. These include: testing behind the sun, testing in deep space, detonating a series of explosions to simulate an earthquake, testing during or soon after an earthquake, testing in large underground cavities, testing in nonspherical cavities, testing in low-coupling material such as deposits of dry alluvium, and masking a test with a large, legitimate industrial explosion. While some of these scenarios warrant genuine attention from a monitoring perspective, others can be dismissed because of extreme difficulty of execution or even infeasibility. To determine which are which, standards of credibility need to be applied.

For an evasion scenario to be credible it must be technically feasible and it must create a worthwhile advantage for the country considering cheating. As discussed in chapter 2, a country considering cheating would have to evaluate the risks and costs of being caught against the benefits if not caught. The country concerned about preventing cheating has to guess the other country's values for making such decisions. While a slight probability of detection might be sufficient to deter cheating, a much more stringent standard is usually needed to achieve high confidence that any cheating would be detected. Thus, the degree of confidence needed to satisfy the concerned country is often higher than what is needed in practice to prevent cheating.

Although the majority of proposed evasion scenarios have been shown to be readily defeated by a good seismic monitoring network, a few concepts have evoked serious concern and analysis on the part of seismologists and other scientists. The remainder of this first section provides a brief listing of the various evasion scenarios. The following three sections discuss in detail evasion scenarios involving cavity decoupling and how opportunities for decoupling could be reduced. The final section assesses the extent to which the most threatening evasion scenarios limit our capability to monitor seismically underground nuclear explosions.

Testing Behind the Sun or in Deep Space

It has been suggested that the Soviet Union could cheat on all test limitation treaties simply by testing in deep space or behind the sun. The idea is that one or two space vehicles would go behind the sun or into deep space. A nuclear device would be detonated and an instrument package would record the testing information and at a later time transmit the data back to Earth. Some feel that such a testing scenario is both technically and economically feasible. Others feel that the technical sophistication, risk, and uncertainty of such a test exceeds the utility of any information that could be obtained in such a manner. Such a test would be an unambiguous violation of several treaties, and hence, discovery would be costly to the tester. In any case, if clandestine testing behind the sun or in deep space is demonstrated on technical grounds to be a concern, the risk could addressed, albeit at considerable expense, by deploying satellites to orbit around the sun. Such satellites equipped with detectors for thermal photons could monitor explosions in deep space. Alternatively, the risk could be addressed politically by negotiating an agreement to conduct simple inspections of the rare vehicles that go into deep space.

Simulating an Earthquake

It has been suggested that a series of nuclear explosions could be sequentially detonated over the period of a few seconds to mimic the seismic signal created by a naturally occurring earthquake. The purpose of such a sequential detonation would be to create a P-wave amplitude that would indicate an earthquake when using the M_s:m_b discriminant.[1] This evasion method has been dismissed, however, because it only works if the P-wave amplitude is measured over just one cycle. If the P-wave amplitude is measured over several cycles, the M_s:m_b discriminant will indicate an explosion. Furthermore, the sequence of waves simulated by the explosion will only appear as an earthquake over a particular distance range. Consequently, a well-distributed network that records over a variety of ranges would not be fooled. In addition, such an evasion attempt would create large seismic signals that other discriminants might recognize as being created by an explosion.

Testing During an Earthquake

The *hide-in-earthquake* scenario posits that a small explosive test can be conducted without detection by detonating it shortly after a nearby naturally occurring earthquake. If the earthquake is sufficiently large and the explosion is properly timed, the seismic signal of the explosion will be partially or completely hidden by the larger seismic signal of the earthquake. This evasion method was at one time considered a challenge to seismic monitoring even though the technical difficulties associated with the execution have long been known to be great. For example, seismologists currently have no reliable techniques for the short-term prediction of the time, location, and size of earthquakes, and this limitation is unlikely to be overcome in the near future.

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[1] A discussion of M_s:m_b and other discriminants is presented in chapter 5, "Identifying Seismic Events."

Recent developments in seismic instrumentation and data handling have further reduced the feasibility of this evasion scenario. New seismic instrumentation is now capable of filtering so as to pass only high-frequency seismic waves. Because nuclear explosions produce higher frequency seismic waves than earthquakes, it is often possible to remove the effects of distant earthquakes and see the waves created by the explosion. For this reason and the difficulty of detonating an explosion at the right location and time, the hide-in-earthquake scenario is no longer considered a credible evasion threat. However, because high-frequency seismic waves may not always be detectable at great distances, it may be necessary to have seismic stations within the Soviet Union to obviate the hide-in-earthquake scenario at yield limits as small as a few kilotons.

Testing in a Large Underground Cavity—Decoupling

If a nuclear explosion is set off in a sufficiently large underground cavity, it will emit seismic waves that are much smaller than those from the same size explosion detonated in a conventional underground test. This scheme, called *cavity decoupling*, has been experimentally verified at small yields. It is the consensus of geologists that significant opportunities exist within the Soviet Union to construct underground cavities suitable for decoupling low yield explosions. Furthermore, it is the consensus of seismologists that seismic waves can be muffled by this technique. Consequently, the technical capability to conduct clandestine decoupled nuclear tests determines the yield threshold below which treaty verification by seismic means alone is no longer possible with high confidence. The later sections of this chapter discuss cavity decoupling scenarios in detail.

Testing in a Nonspherical Cavity

This evasion scenario suggests that the detonation of an explosion in an nonspherical cavity could be used to focus the resulting seismic waves away from monitoring stations. This evasion scenario has been dismissed for two reasons. First, a nonspherical cavity would have no better and perhaps worse decoupling than a spherical cavity of the same volume.[2] Second, a monitoring network would have seismic stations in many directions, not just one. The presence of such stations would increase the risk of detection by at least one station, possibly at an enhanced level.

Testing in Low-Coupling Materials

As discussed in the previous chapters, the proportion of explosive energy converted into seismic waves depends on the type of rock in which the explosion occurs. Low-coupling materials such as dry porous alluvium have air-filled pore spaces that absorb much of the explosive energy. This has led to the concern that a monitoring network could be evaded by detonating an explosion in low-coupling material.

The opportunities for such evasion are thought to be limited in the Soviet Union because no great thicknesses of dry alluvium are known to exist there. In fact, large areas of the Soviet Union are covered with permafrost that would produce well-coupled seismic signals. Estimates of the maximum thickness of alluvium in the Soviet Union indicate that it would only be sufficient to muffle explosions up to 1 or 2 kt. Even if such an opportunity does exist, alluvium is a risky medium for testing because it is easily disturbed. An explosion in alluvium could create a subsidence crater or other surface expression. Consequently, clandestine testing in low-coupling material is considered feasible only for explosions below 1 or 2 kt.

Masking a Test With a Large Chemical Explosion

As discussed in chapter 5, chemical explosions are used routinely in the mining and construction industries. In monitoring a low-yield or comprehensive test ban treaty, there would be concern that large chemical explosions could be used to mask the signals from a nuclear test. Unlike an earthquake, such explosions could be timed to coincide with a clandestine nuclear test. If done in combination with cavity decoupling, this evasion scenario would be a challenge to a monitoring network. For example, a nuclear explosion of a few kt could be decoupled in a large underground cavity and the reduced seismic signal either masked with the simultaneous detonation of a very large chemical explosion or attributed to a chemical explosion. The combination of decoupling and masking is discussed further in the detailed sections on decoupling scenarios.

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[2] L.A. Glenn and J.A. Rial, "Blast-Wave Effects on Decoupling With Axis-Symmetric Cavities," *Geophysical Journal of the Royal Astronomical Society*, October 1987, pp. 229-239.

PHYSICS OF CAVITY DECOUPLING

An underground nuclear explosion creates seismic waves with a broad range of frequencies. For purposes of seismic detection and identification of small events, frequencies from roughly 1 Hz to perhaps as high as 30 or 50 Hz may be important.

For the lower end of this frequency range, the amplitude or size of the seismic waves created by an explosion is approximately proportional to the total amount of new cavity volume created by the explosion. A conventional, or tamped, test is detonated in a hole whose initial volume is negligible compared to its post-test volume. Because the initial hole is small, the rock surrounding the explosion is driven beyond its elastic limit by the explosion and flows plastically. This flow results in large displacements of the surrounding rock mass, and therefore leads to a large cavity-volume increase around the explosion, and efficient generation of seismic waves.

If, on the other hand, the explosion occurs in a hole of much greater initial volume, the explosive stresses at the cavity wall will be smaller. This results in less flow of the rock, hence less cavity expansion and reduced coupling to seismic waves. If the initial hole is sufficiently large that the stresses in the surrounding rock never exceed the elastic limit, the seismic coupling is minimized. Further increase of the emplacement hole size will not further reduce coupling at low frequencies, and the explosion is said to be *fully decoupled*.

Cavity construction on a scale required for explosion decoupling is possible in either salt of sufficient thickness or in hard rock such as granite. In either case, the cavity volume required for full decoupling increases in proportion to the explosion yield and decreases as the strength of the rock increases.

EFFICIENCY OF CAVITY DECOUPLING

Limits on Cavity Construction in Salt Deposits

Large cavities suitable for decoupled nuclear testing above 1 kt can be constructed in salt deposits either by detonating a nuclear explosion of several tens of kilotons, or by solution mining. For example, a stable, free-standing cavity was created by the U.S. "Salmon" test, a 5.3 kt explosion in a salt dome.[3] This cavity was sufficiently large to decouple the subsequent 0.38 kt "Sterling" nuclear test, which was detonated in the Salmon explosion cavity.[4] Nuclear explosions create cavity volume approximately in proportion to their yield. Thus, applying the yield ratio given in the Salmon/Sterling experiment, an explosion greater than 14 kt would be required to create a cavity sufficient to fully decouple a 1 kt test; similarly, an explosion greater than 140 kt would be required to create a cavity sufficiently large to fully decouple a 10 kt test. Explosive construction of cavities adequate to decouple shots above 1 kt would obviously be impossible to accomplish clandestinely. Past nuclear tests in the Soviet Union have produced many cavities suitable for decoupling, but the location and approximate size of most of these is known; and thus evasion opportunities at these sites could be limited if activity at them is monitored.

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[3] U.S. Department of Energy, Office of Public Affairs, Nevada Operations Office, *Announced United States Nuclear Tests, July 1945 Through December 1983*, NVO-209 (rev.4), January 1984.

[4] Ibid.

Solution mining on the required scale would also be difficult to conceal. For example, with present techniques it would take many months or perhaps even a year of continuous operation at high circulation rates to solution mine a cavity adequate to fully decouple a 5 kt explosion. The technology also requires enormous amounts of water and the disposal of enormous amounts of brine, further hindering concealment. However, given that such an operation would be detected and monitored, it might be difficult to distinguish legitimate and evasion-related activity. Concealment of the site would not be necessary if appropriate activity (mining of salt) exists. Consequently, areas of salt deposits might require treaty provisions dealing with chemical explosions with magnitudes comparable to decoupled nuclear explosions.

Apart from the significant problems of concealment and resource application, there do not appear to be constraints preventing the construction, by solution mining, of cavities large enough to fully decouple explosions up to 10 kt. In fact, the Soviet literature reports solution-mined cavities with volumes up to one million cubic meters. If such a cavity could be constructed with a spherical shape, it would be 60 meters in radius. A spherical cavity with a 60 meter radius would have sufficient volume to decouple an explosion up to 14 kt, based on cube root scaling of the U.S. Salmon/Sterling salt dome decoupling experiment. However, these existing large, solution-mined cavities are not spherical. They are highly elongated, irregular in shape, and filled with brine. These features reduce the size of the explosion that could be decoupled in the cavity. Furthermore, the brine in the cavity supports through its own hydrostatic pressure a considerable portion of the overburden (i.e. the weight of the overlying rocks). If the cavity was empty, the overburden pressure would not be supported and the stability of the cavity would be uncertain.

Both salt domes and bedded salt regions have to be considered as candidate locations for construction of decoupling cavities in salt, although the mining procedure would be more complex in bedded salt deposits. To create a cavity in bedded salt, solution mining of soluble layers would have to be combined with explosive mining of insoluble interbeds.

The creep strength of natural rock salt controls the maximum depth at which a stable cavity can be maintained. Cavity collapse or major changes in cavity shape occur over time scales of a few months when the overburden pressure at cavity depth exceeds the internal pressure in the cavity by more than about 20 MPa (200 times atmospheric pressure). This corresponds to a maximum depth of about 1 km for a stable, empty cavity. A brine-filled or gas-pressurized cavity might be stable to about 2 km depth. If a cavity is made by an explosion or by solution mining, the salt will be weakened. This will be a consideration because for weak salt a larger cavity is needed, than predicted for strong salt, to fully decouple a given explosion.

Limits on Cavity Construction in Hard Rock

No cavities have been constructed in hard rock on the scale of those known in salt. There is agreement among verification experts that decoupling cavities with radii up to about 25 meters, suitable for repeated testing up to about 1 or 2 kt, can probably be constructed with existing technology. Repeated testing could likely be detected well enough to get good locations; and the detection of repeated events at the same location would be suspicious. There appear to be no known technological limitations preventing construction of cavities up to perhaps 45 meters radius, suitable for decoupling explosions up to about 10 kt. However, the long-term stability under repeated explosive loading is questionable.

In constructing a cavity of radius larger than about 25 meters, a very extensive network of long cables would be needed to strengthen and pre-stress a large region of the rock surrounding the cavity. Such construction would require an elaborate network of additional tunnels and shafts in the surrounding rock. The technology is untested on this scale and construction may be severely complicated in many areas by the presence of high compressive stresses in the rock and by joints, fractures, and other rock inhomogeneities that are present in even the most uniform granites.

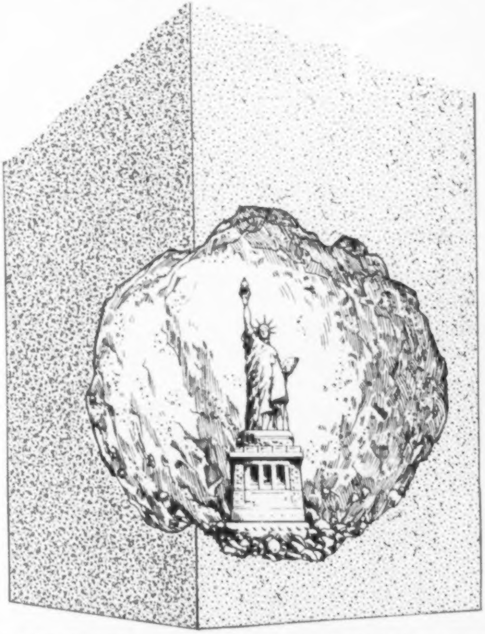
Concealment of such a massive excavation operation from satellite reconnaissance or other National Technical Means would be extremely difficult, and thus some plausible cover operation would probably be necessary. A potential evader would also have to consider the possible leakage along joints of radioactive products such as bomb-produced noble gases. Finally, the evader would also have to be concerned that explosions might result in the unexpected collapse of the cavity and the formation of a crater on the surface. Such a possibility is not without precedent: in the 1984 "Midas Myth" test in Nevada, 14 people were hurt and one man killed during the unexpected formation of a crater above a tiny collapsed cavern at a depth of 1,400 feet.

Cavity Size Requirement for Decoupling

The minimum cavity radius required for full decoupling is proportional to the cube root of the explosion yield and inversely proportional to the cube root of the maximum pressure which the overlying rock can sustain without blowing out or collapsing. In salt, the maximum sustainable cavity pressure increases approximately in proportion to depth. Therefore, the minimum cavity size for decoupling is inversely proportional to the cube root of depth (i.e. smaller cavities will work at deeper depths). As noted above, however, there is a limit to how deep a cavity can be maintained in salt, due to salt's low creep strength. Thus, there are two separate issues regarding the depth of cavities: 1) the deeper the cavity, the smaller the size required to decouple an explosion of a given yield, and 2) the deeper the cavity, the lower the strength of the salt and the more difficult it is to maintain an open cavity. The low strength of salt eventually limits the depth at which a cavity can be created. Even the smallest hole below 1-2 km will squeeze shut.

As discussed earlier, the limiting depth for stability of a large, empty cavity in salt is about 1 km. This depth implies that the Salmon/Sterling cavity (at 0.82 km depth), was very near the maximum depth for stability of an empty cavity. Consequently, the Salmon cavity size approximately sets the lower bound on

Figure 6-1.—Minimum Cavity Size Required To Decouple a 5 kt Nuclear Explosion



To fully decouple a 5 kt explosion in salt, a spherical cavity with a radius of at least 43 meters would be required. The height of the Statue of Liberty with pedestal (240 ft) is 85% of the required diameter (282 ft).

SOURCE: Office of Technology Assessment, 1988.

cavity size for full decoupling (at the yield of the Sterling test). This implies a minimum cavity radius of at least 25 meters for full decoupling of a 1 kt test in salt. Cavity requirements are expected to scale as the cube root of the explosion yield. For example, to fully decouple a 5 kt explosion in salt, a spherical cavity with a radius of at least 43 meters (25 times the cube root of 5) would be required (figure 6-1).

In granite, a smaller cavity, perhaps around 20 meters in radius, might be expected to successfully decouple a 1 kt explosion, while a 34 meter cavity would be needed to decouple 5 kt. This number is a rough estimate because it does not take into account the joints and fractures that would be present in even the most uniform granites. The difference between the salt and granite estimates is due to the greater strength of granite, which might therefore sustain a somewhat higher pressure. Such estimates, however, remain uncertain and some experts doubt that the effective strength of granites would be greater than salt and believe that a radius comparable to that of salt would be needed to decouple the same size explosion in granite.

CONSTRAINTS ON DECOUPLING

Decoupling Factors

The reduction of seismic wave amplitudes achievable by full decoupling is called the *decoupling factor*. On theoretical grounds, the decoupling factor is expected to be smaller at high frequencies than at low frequencies.[5] This expectation has been confirmed experimentally. The transition from low-frequency decoupling to high-frequency decoupling occurs over a range of frequencies rather than abruptly, and the transition frequency range depends on yield. For a 1 kt explosion, seismic waves of about 6 Hz and below can be assumed to be controlled by the full low-frequency decoupling factor, whereas seismic waves above 6 Hz will exhibit much less decoupling.

Low Frequencies

Several decoupling experiments have been carried out by the United States. Taken together, these experiments permit us to estimate the low-frequency decoupling factor with considerable confidence. In the 1966 Salmon/Sterling experiment, a smaller nuclear explosion was detonated in the cavity created by a larger explosion. Analysis of the seismic waves from these events led to the conclusion that the low-frequency decoupling factor is approximately 70. That is, a fully decoupled explosion in salt has its low-frequency seismic amplitude reduced by a factor of 70 compared to a "tamped," or "well-coupled," explosion of the same yield in salt. The 1985 Diamond Beech/Mill Yard experiment compared decoupled and tamped nuclear explosions in tuff. In this case, the observed decoupling factor was again 70. The 1959 Cowboy series of tests in dome salt used conventional explosives instead of nuclear explosives. While initial estimates of the decoupling factor from Cowboy ranged from 100 to 150, it was subsequently determined that conventional explosives are significantly less efficient when detonated in a large cavity than when detonated under tamped conditions. When a correction was made for this effect, the Cowboy data yielded an estimate of the full low-frequency decoupling factor of approximately 70, in close agreement with the results obtained in the nuclear experiments.

Earlier theoretical estimates that the low-frequency decoupling factor could be as high as 200 or greater were based on several simplifying assumptions. **Seismologists are now in agreement that the experimentally determined decoupling factor of 70 is appropriate at low frequencies.**

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[5] Donald B. Larson (ed.), Lawrence Livermore National Laboratory, *Proceedings of the Department of Energy Sponsored Cavity Decoupling Workshop, Pajaro Dunes, California*, July 29-31, 1985.

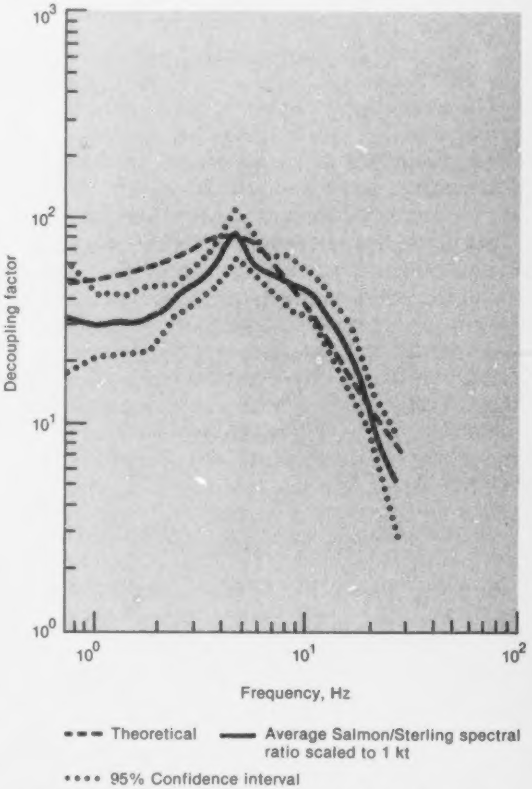
High Frequencies

Roughly speaking, if two explosions excite low-frequency seismic waves whose amplitudes differ by a factor F, their high-frequency seismic waves are expected to have amplitudes whose ratio is approximately the cube root of F. Thus, seismic theory predicts that the decoupling factor will be much reduced at high frequencies. The Salmon/Sterling experimental data corroborate this prediction. Figure 6-2 shows the decoupling factor as a function of frequency inferred from the Salmon/Sterling experiment, with both explosions scaled to 1 kt. As already discussed, the low-frequency decoupling factor averages about 70. However, the experimentally observed decoupling factor begins to drop at about 6 to 8 Hz, and the drop is quite sharp above about 10 Hz. **At 20 Hz, the decoupling factor is down to approximately 7.** This result can reasonably be extrapolated to estimate decoupling for other yields by scaling the frequency axis in figure 6-2 by the inverse of the cube root of yield. For example, a 5 kt explosion would be expected to be decoupled by a factor of approximately 7 at a frequency of about 12 Hz (20 divided by the cube root of 5). These scaling considerations provide an additional argument in favor of using high-frequency recordings to extend monitoring capabilities down to lower yield levels.

At this time, the exact value of the high-frequency decoupling factor is considered less certain than the low-frequency factor because the instruments recording the Salmon explosion lacked sufficient dynamic range to provide reliable data above 20 Hz. High-frequency data from the Diamond Beech/Mill Yard experiment in tuff also show high-frequency decoupling factors less than 10, consistent with the Salmon/Sterling experience in salt. However, interpretation of the Diamond Beech/Mill Yard data in terms of decoupling is complicated by the facts that the decoupled event was a factor of 100 smaller than the tamped event, the decoupling cavity was hemispherical, the measurements were made at short distances, and the events were not co-located. Data from a better experiment could reduce the uncertainty in the high-frequency decoupling factor.

The evidence for reduced decoupling at high frequencies comes from experiments with spherical (or hemispherical) cavities. However, theoretical calculations show that this conclusion is not altered even when highly elongated

Figure 6-2.—Decoupling Factor as a Function of Frequency



The experimentally observed decoupling factor decreases at higher frequencies.

SOURCE: Modified from J.R. Murphy, Summary of presentation at the ARPA Decoupling Conference, Feb. 7, 1979.

cavity geometry is considered, that is, it does not appear to be possible to increase the high-frequency decoupling factor by constructing specially shaped, air-filled cavities.[6] An evacuated, elongated decoupling cavity may enhance high-frequency decoupling in certain preferred directions, but will decrease high-frequency decoupling in other directions.

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[6] Glenn and Rial, op. cit., footnote 2.

DECOUPLING OPPORTUNITIES IN THE SOVIET UNION

Cavity construction for low-yield decoupling is possible in salt domes, bedded salt, and dry hard rock. These geologic categories exclude few areas of the Soviet Union. However, it is generally agreed that salt domes provide the most suitable host rock for large, stable cavities. Salt domes are the most suitable because of the homogeneity of rock salt in domes, the relative simplicity compared to hard rock of constructing stable cavities explosively or by solution mining, and the fact that numerous large cavities already exist in salt domes in the Soviet Union. Cavities confined to a single, homogeneous salt layer in bedded salt, on the other hand, are limited in size by the layer thickness. Assuming that the radius of a cavity in bedded salt should not exceed one-half the layer thickness, **decoupling opportunities are probably limited to 1 or 2 kt in bedded salt.**

Vast regions of the Soviet Union are underlain by salt deposits. The general distribution of these deposits is indicated by the map in figure 6-3. However, we probably do not know the full extent of Soviet salt deposits. Furthermore, although figure 6-3 indicates those areas where salt domes are prevalent, without access to detailed subsurface geologic data it is not possible to rule out the presence of domes in any area of bedded salt in the Soviet Union.

Because the construction of large salt dome cavities may be difficult to conceal, it is useful to estimate the decoupling opportunity provided by already existing cavities created by Soviet underground explosions (presumed tamped). Table 6-1 summarizes this information. At each yield level, the table shows the number of existing holes large enough for full decoupling. These numbers refer to cavities presumed to have remained open following the largest known Soviet salt dome explosions. The yields in table 6-1 were estimated by dividing the seismically estimated yields of the largest Soviet salt dome explosions by the Salmon/Sterling yield ratio (5.3/0.38 = 14). The use of this ratio is justifiable because the cavity volume created by a tamped explosion (in this case 5.3 kt, Salmon) is proportional to yield and the largest fully decoupled explosion (in this case 0.38 kt, Sterling) is proportional to cavity volume.

Table 6-1 indicates that Soviet decoupling opportunities at 1 kt and above, using existing explosion-generated cavities, are limited to three regions: the North Caspian region, the East Siberian Basin, and a single site in Central Asia. On the basis of table 6-1, there are

Table 6-1.—Numbers of Decoupled Explosions of Yield Greater Than 1 kt That May Be Possible in Cavities Created by Contained U.S.S.R. Underground Explosions, 1961-86[a]

	Yield (kt)				
Areas of known salt deposits	1	2	3	4	5[b]
North Caspian region:					
Azgir	2	4	2	0	
Astrakhan[c]	1	—	—	—	0
Orenburg	2	—	—	—	0
Karachaganak	—	5	—	—	0
Lake Aralsor	—	1	—	—	0
Ishimbay	—	—	—	1	0
East Siberian Basin:					
NW of Lake Baikal	3	2	—	—	0
Within a few x 100 km of basin	1	—	—	1	0
Bukhara, Central Asia (explosion used to extinguish fire in oil well)	—	—	—	1	0

Full decoupling in salt: minimum radius (meters) = 25 • (explosive yield (kt))$^{1/3}$

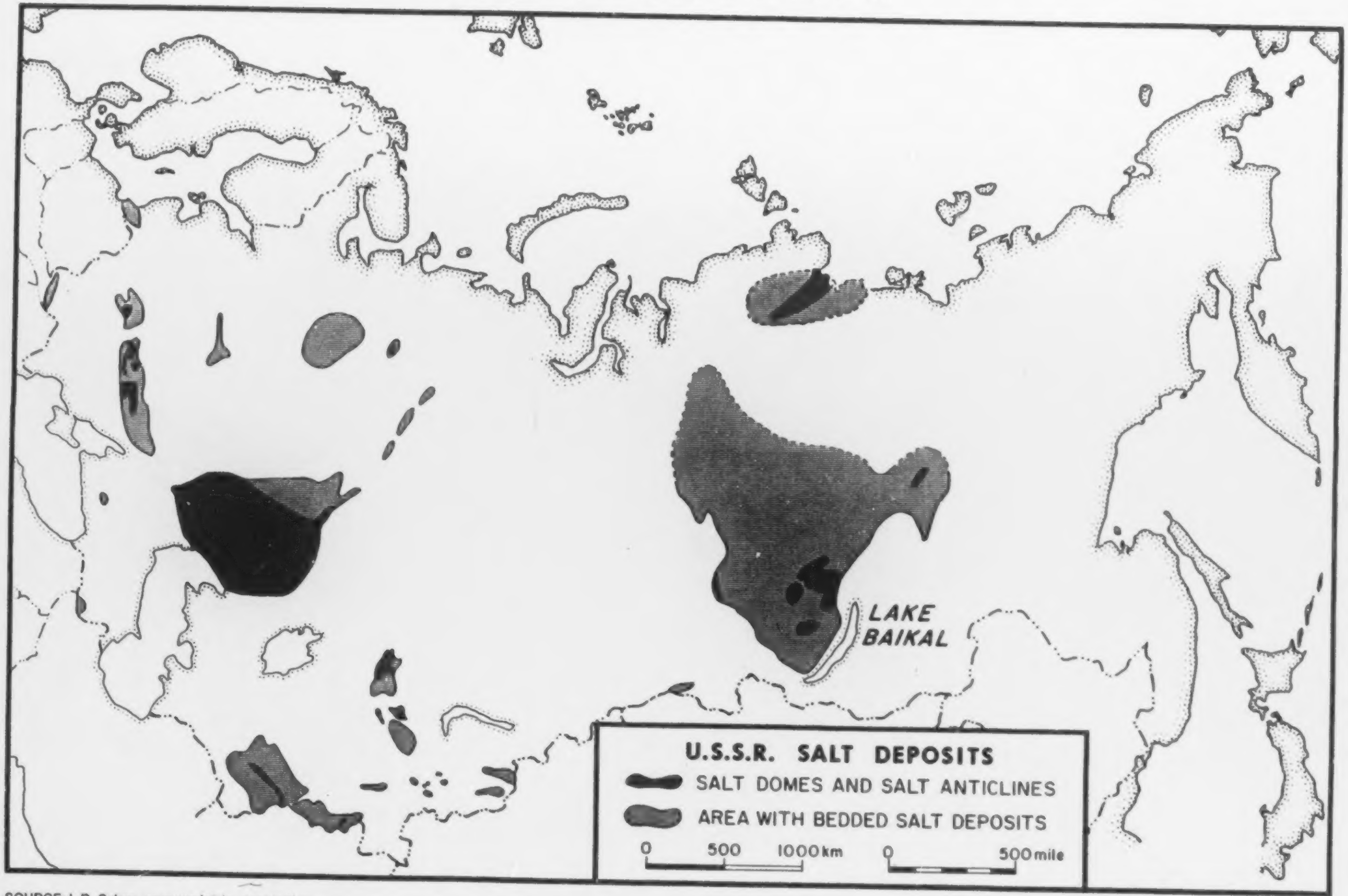
Full decoupling in hard rock: minimum radius (meters) = 20 • (explosive yield (kt))$^{1/3}$

[a] Obtained from yield of known explosion at site divided by yield ratio for Salmon/Sterling = 5.3/0.38 = 14.

[b] (or greater)

[c] Many cavities capable of being used for full decoupling at yields of about 0.5 kt; some could be connected.

Figure 6-3.—Salt Deposits in the Soviet Union


LAKE BAIKAL
U.S.S.R. SALT DEPOSITS
SALT DOMES AND SALT ANTICLINES
AREA WITH BEDDED SALT DEPOSITS
0
500
1000 km
0
500 mile

SOURCE: L.R. Sykes, manuscript in preparation.

no opportunities in existing explosion-generated cavities above 4 kt. It should be noted that the potential decoupled yields estimated in table 6-1 depend critically on seismic yield estimates made for the corresponding cavity-generating explosions. The seismic yield estimation procedure used in constructing table 6-1 is one that most seismologists would support, within an uncertainty of about 50 percent. This uncertainty translates into 50 percent uncertainty in the decoupled yields in table 6-1.

PARTIAL DECOUPLING

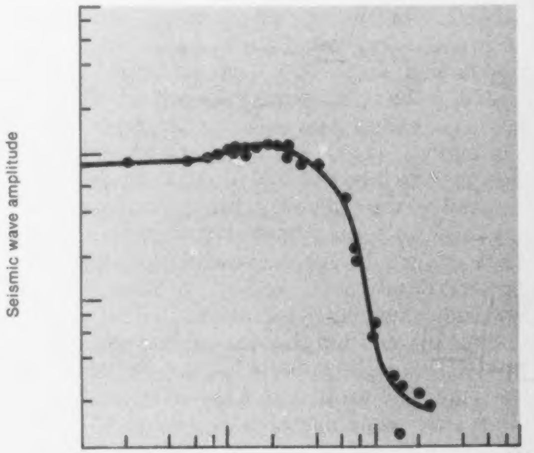
The size of an explosion that could be decoupled is limited by the maximum size of an air-filled cavity that could reasonably be created and remain stable. Concern has been expressed, however, that even if a nuclear device is too large to be fully decoupled, it could perhaps be *partially* decoupled, thus reducing its seismic signal to some extent. It has been further suggested that by partially decoupling large explosions, a country might be able to clandestinely test above the 150 kt threshold level of the Threshold Test Ban Treaty. As figure 6-4 illustrates, however, partial decoupling is not straightforward.

Figure 6-4 is scaled for the case of a 1 kt explosion and shows how the size of the seismic signal is affected by partial decoupling. As the cavity size first increases, the seismic signal actually gets **larger**, reaching a maximum for a cavity about 2 meters in radius. The large seismic signal is produced at first in a small cavity because less energy goes into melting rock and more energy is transmitted into seismic waves. For the case of a 1 kt explosion, the radius has to exceed about 4 meters before any reduction of the seismic signal occurs, and must exceed about 6 meters to obtain reduction by more than a factor of 2. After that, further reduction occurs rapidly. If the relationship for a 1 kt explosion is extrapolated to larger explosions, the radius (in meters) of the cavity to begin partial decoupling = 6 * [size of explosion (kt)]$^{1/3}$. For a 10 kt explosion, the size of the cavity required to begin partial decoupling would be 6 * $10^{1/3}$ = 13 meter radius; for 150 kt, the radius would have to exceed 32 meters.

Conducting a partially decoupled explosion also has many risks that the potential evader would have to consider, including the following:

A. Partially decoupling a nuclear explosion is uncertain. As seen in figure 6-4, the reduction in seismic signal occurs along a steep curve. It would be difficult to predict from such a steep curve how much actual decoupling there will be for a given explosion. If partial decoupling is not achieved, an explosion inside a cavity

Figure 6-4.—Partial Decoupling Effect



The effect of partial decoupling scaled for the case of a 1 kt explosion.

SOURCE: Modified from R.W. Terhune, C.M. Snell, and H.C. Rodean, "Enhanced Coupling and Decoupling of Underground Nuclear Explosions," LLNL Report UCRL-52806, Sept. 4, 1979.

might actually produce seismic signals larger than a *well-coupled* explosion.

B. Partial decoupling creates greater pressure on the wall of a cavity than full decoupling. For example, a 20 kt explosion set off in a cavity suitable for full decoupling of 10 kt will result in a doubling of the cavity pressure compared to that for the 10 kt shot. Partial decoupling damages the cavity wall and this makes it more difficult to be confident that noble gases and other bomb-produced isotopes will not leak out of the cavity, reach the surface, and be detected. A 20 kt explosion would have to be detonated in a cavity near the maximum possible depth to minimize the pressure on the cavity wall. Risks of deformation or collapse increase with both the yield and the depth of the cavity. A risk trade off would be involved: the desire to minimize the escape of bomb-produced gases leads the evader to construct a cavity as deep as possible, whereas construction difficulties, the time needed for construction, and the risk of cavity deformation or collapse all become increasing problems at greater depths.

MONITORING CAPABILITIES CONSIDERING EVASION

The previous two chapters discussed the various thresholds for the detection and identification of seismic events within the Soviet Union. These thresholds, combined with the feasibility of successfully conducting clandestine decoupled nuclear explosions, effectively determine what levels of nuclear test restrictions can be monitored with high confidence.

As discussed in chapters 4 and 5, well-run seismic monitoring networks can detect and identify underground nuclear explosions with yields well-below 1 kt if no attempt is made to evade the monitoring network. However, a country wanting to test clandestinely above the allowed threshold would presumably attempt to reduce the size of the seismic signal created by the explosion. For example, a country might attempt an evasion scenario where the explosion is secretly decoupled in a large underground cavity and the muffled signals are then masked by or attributed to a large chemical explosion that is simultaneously detonated under the guise of legitimate industrial activity. The problem for the monitoring network is to demonstrate a capability to distinguish such an evasion attempt from the background of frequent earthquakes and legitimate industrial explosions that occur at low yields.

The monitoring burden placed on the seismic network by various evasion scenarios can be greatly lessened if seismology gets some help. Countering the various evasion scenarios needs to be approached through a combination of seismic methods, treaty constraints, and other monitoring methods that reduce the difficulties and uncertainties of applying seismic monitoring methods to every conceivable test situation. Specifically, the structure of any treaty or agreement should create a testing environment such that a combination of prohibitions, inspections, and seismic methods will provide the desired high levels of verification capability. Examples of the type of treaty constraints that have been proposed to improve the capability of various monitoring networks include the following:

- **Limitations on Salvo-Fired Chemical Explosions:** All large salvo-fired chemical explosions above a certain size (depending on the threshold being monitored and the area) would be limited and announced well in advance with inspections/monitoring to be conducted on-site by the monitoring side at their discretion.
- **Limitations on Ripple-Fired Chemical Explosions:** All ripple-fired chemical explosions above a certain size (depending on the threshold being monitored and the area) would be announced in advance with a quota of on-site inspections available to the monitoring party to be used at their discretion.

- **Limitations to One Inspected and Calibrated Test Site:** All tests would be conducted within the boundaries of one defined test area in hard rock or below the water table. Further, several calibration tests recorded by in-country monitoring stations would be allowed with yields spanning the threshold yield. Inspections of the test site would be allowed before enactment of the treaty to ensure that no large cavities suitable for decoupling were present.
- **On-going Test Site Inspections:** A yearly quota of on-site inspections by the monitoring party would be allowed at the designated test site.
- **Joint On-site Inspections of Sites of Possible Violations:** A yearly quota of on-site inspections would be allowed at sites designated by the monitoring party with prompt access by a U.S.-Soviet technical team.
- **Country-wide Network Calibration Tests:** Agreement to conduct a number of large chemical explosions, of both salvo and ripple-fired types, would be allowed to evaluate signal propagation characteristics and detection-identification capabilities in particular critical areas.

If these types of testing constraints can be negotiated within a treaty, reduced thresholds could effectively be monitored. Keeping in mind the various types of networks and negotiated treaty constraints that are possible, the following sections give a sense of the treaty thresholds that could be monitored.

Monitoring Capability Within The U.S.S.R. Using No Internal Stations

The threshold for detecting and locating seismic events within the Soviet Union (90 percent probability of detection at four or more stations), using a seismic network with no internal stations, is at least as low as m_b 3.5 (ch. 4). The associated threshold for the *identification* of 90 percent of all seismic events within the Soviet Union is at least as low as m_b 4.0 (ch. 5). An m_b of 4.0 corresponds to a well-coupled nuclear explosion with a yield of about 1 kt. Consequently, clandestine nuclear explosions above 1 kt would need to be decoupled to evade the monitoring network. Several considerations limit the threshold at which such clandestine nuclear tests might be attempted.

Holes large enough to decouple explosions above a few kilotons would have to be made in salt domes. Almost all of the known salt dome regions of the U.S.S.R. and regions that have any known types and thicknesses of salt deposits are situated in areas of low natural seismicity and good seismic transmission. The detection of seismic events from such areas would probably be better than average.

Even if an explosion were successfully decoupled and the seismic signal muffled down below the 90 percent identification threshold, it might still be identified. Decoupled explosions produce seismic signals that are very *explosion-like*. Because there is no breaking of rock or tectonic release, the signals from decoupled explosions do not look like earthquakes. This makes the identification of a detected event as a decoupled explosion likely. Even though the magnitude of the clandestine test is below the *identification* threshold, the test would in many cases still be well-detected and located. Also, note that the identification threshold is for 90 percent identification, that is, 90 percent of all events above this magnitude will be positively identified. There is no sharp boundary between identification and non-identification. Even if the seismic magnitude from a specific event fell somewhat below the identification threshold, there is a good chance that it would be identified. As discussed earlier, the identification threshold is largely set by the problem of distinguishing large chemical explosions from small decoupled nuclear explosions, so that treaty constraints for handling large chemical explosions would be very helpful.

The largest air-filled cavity that could reasonably be created and remain stable would fully decouple a nuclear explosion of no more than about 10 kt. While large explosions of up to 20 or more kt could theoretically be partially decoupled to produce a seismic signal below the cautious identification threshold, such evasion scenarios are considered implausible because of the practical considerations of containment and predicting the decoupling. In fact, evasion scenarios for explosions above 10 kt are not considered credible by most experts. This means that the monitoring of the Soviet Union with only an external network can be accomplished down to a threshold of about 10 kt. However, for accurate monitoring of a 10 kt treaty, all experts agree that it would be desirable to have stations within the Soviet Union for accurate yield estimation, plus treaty restrictions for handling the identification of large chemical explosions in areas where decoupling could take place.

Monitoring Capabilities Within The U.S.S.R. With Internal Stations

The detection threshold (90 percent probability of detecting a seismic event at four or more stations) is m_b 2.0 - 2.5 using a seismic network with internal stations (ch. 4). The associated threshold for the identification of 90 percent of all seismic events is at least as low as m_b 3.5 (ch. 5) and could be reduced depending on what provisions are negotiated to handle chemical explosions. This identification threshold corresponds to a well-coupled nuclear explosion with a yield below 1 kt.

Seismic stations within the Soviet Union would permit lower thresholds to be monitored by reducing the opportunities for evasion. Decoupling is possible for explosions with yields below 10 kt. Consequently, the network of internal stations would be designed primarily to reduce the opportunities for decoupling. The most challenging evasion scenario for such a network would be the situation where a small (1-5 kt) nuclear explosion is decoupled and the reduced seismic signal masked by or attributed to a simultaneous detonation of a legitimate industrial explosion. As noted above, several considerations limit the threshold at which such clandestine nuclear tests might be attempted.

Almost all of the known salt dome regions of the U.S.S.R. and regions that have any known types and thicknesses of salt deposits are situated in areas of low natural seismicity and good seismic transmission. The exceptions include salt deposits in the Caucasus, Tadjikistan, and near the Chinese border. An internal monitoring network should involve the placement of more seismic stations at closer spacing in those few areas. In addition, those areas are all near the southern border of the U.S.S.R. where the detection and identification thresholds either are currently better or can be made better than the average identification threshold by monitoring from nearby countries (i.e., Turkey for Caucasus) and stations inside the U.S.S.R.

Many seismologists feel that the discrimination threshold of m_b 3.5 is too cautious a prediction for the capability of an internal seismic network. This identification threshold is mostly set by the large numbers of chemical explosions that occur below this level. The limitations imposed by identifying chemical explosions can be approached in two ways: first, limiting them by treaty (limiting their size and requiring on-site observers and monitoring) and second, by further developing techniques to make use of the expected differences between the signals created by distributed ripple-fired chemical explosions and the concentrated point explosions characterizing decoupled nuclear tests. While chemical explosions in the U.S.S.R. of m_b 3.0 are likely to be more common than those of m_b 3.5, the monitoring need only be concerned with those chemical explosions of m_b 3.0 and larger that are located in areas of known or possible salt domes. This excludes very large areas of the Soviet Union. A monitoring network with stations internal to the Soviet Union should concentrate on areas of poor transmission and areas where decoupling opportunities would be possible. Through such a strategy and with constraints on chemical explosions, many predict that the identification threshold will be closer to m_b 3.0. This would significantly reduce the size of decoupled explosions that could be clandestinely attempted.

All of the considerations so far have not made allowances for increased verification capability afforded by high-frequency recording. The recent N.R.D.C. recordings to very high frequencies at distances of 200 - 650 km from three chemical explosions with yields of 0.01 - 0.02 kt are very impressive in this regard. From these data, it appears that explosions with yields comparable to a fully decoupled 2.6 - 3.8 kt explosion (corresponding to magnitude m_b 3.0) in areas of good transmission will produce large signals with frequencies of 10 - 20 Hz. This is also a frequency band in which the decoupling factor will be small.

The decoupling reduction that is assumed for these evasion scenarios is a factor of 70. If the monitoring system has even a modest capability to record frequencies as high as 10 - 15 Hz, the effectiveness of the decoupling would be greatly reduced. Figure 6-2 indicates a decoupling factor of 30 for frequencies of 1 - 2 Hz and 50 as averaged from 1 to 5 Hz. At high frequencies, the decoupling factor will probably be reduced from 70 to below 10. Smaller decoupling factors will result in a lower (better) threshold for the detection and identification of decoupled explosions of a given yield.

Decoupling combined with masking remains a challenging evasion scenario even with a high-quality internal network. Opportunities for such evasion, however, would be limited by the many practical considerations described above and throughout this report. Attempting evasion by this complicated scenario would entail further risk when viewed in conjunction with all types of intelligence gathering, rather than purely as a problem for seismic discrimination. Detected seismic events in areas of possible decoupling would be suspicious and presumably focus attention. On-site inspections could play an important role as opportunities for cheating could be still further reduced by negotiated agreements requiring prior announcement and possible on-site inspections of large chemical explosions in areas of potential decoupling.

Small differences of opinion concerning monitoring capability will always remain because parts of the debate are comparable to discussions of "half-full" versus "half-empty" glasses of water. Some will review the complex operation of seismic monitoring and will conclude that a country could cheat if any step in the process is uncertain. The chain is only as good as its weakest link. Others will review the complicated evasion scenarios that have been postulated and conclude that evasion is too difficult and uncertain to be credible. Cautious assumptions about seismic monitoring capability and generous assumptions about the likelihood of successfully conducting clandestine decoupled nuclear explosions can be combined to produce the conclusion that even with an internal network an explosion of up to 10 or 20 kt could be partially decoupled in the largest hole (capable of fully decoupling a 10 kt explosion) to create a seismic signal below the m_b 3.5 identification threshold. On the other hand, generous assumptions about monitoring capabilities and favorable assumptions about uncertainty and the role of other intelligence gathering systems can be combined to produce the conclusion that even explosions of a fraction of a kiloton fully decoupled can be effectively monitored with high confidence. Considering all of the arguments, however, a few general statements can still be made concerning monitoring capability with an internal seismic network.

Most experts agree that a high-quality network of internal stations combined with stringent treaty constraints, could monitor a threshold of around 5 kt. Differences of opinion range from 1 to 10 kt and are due to judgments about the level of constraints that can be negotiated into the treaty and what levels of motivation and risk the Soviet Union would be willing to take to test clandestinely slightly above the threshold. Experts further agree that below 1 - 2 kt, monitoring would become much more difficult because additional methods of evasion are possible. Explosions of 1 or 2 kt could be decoupled not only in salt but also in other media such as granite and alluvium. At present, there is not a consensus that an internal network would be capable of positively identifying with high confidence all such evasion attempts. If such a capability is possible, it will require demonstration through practical experience of low-yield monitoring within the Soviet Union together with a high level of negotiated supplementary measures to limit certain evasion opportunities.

Chapter 7

Estimating the Yields of Nuclear Explosions

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Chapter 7

Estimating the Yields of Nuclear Explosions

For treaties that limit the testing of nuclear weapons below a specific threshold, the yield of the explosion must also be measured.

INTRODUCTION

Once a seismic event has been detected and identified as a nuclear explosion, the next step is to estimate the yield of the explosion. This is particularly important for monitoring treaties that limit the testing of nuclear weapons below a certain threshold. The process of estimating the yields of Soviet explosions involves three steps: 1) calculate the magnitude of the seismic signal; then, 2) make corrections to adjust for the different geology at each test site; and finally, 3) convert the magnitude into a yield estimate.

The final yield measure describes the explosive energy of a nuclear explosion in terms of kilotons, where 1 kiloton (kt) was originally defined as the explosive power equivalent to 1,000 tons of TNT. This definition was found to be imprecise,[1] however, and so it was agreed in the United States during the Manhattan project that the term "kiloton" would refer to the release of 10^{12} calories of explosive energy.

$$1 \text{ kiloton} = 1{,}000{,}000{,}000{,}000 = 10^{12} \text{ calories}$$

While this convention is also followed in the Soviet Union, it does not necessarily mean that the United States and the Soviet Union calculate explosive yields in the same way. Only that part of the total energy released in a nuclear explosion that is immediately available (the so-called *prompt energy release*) is counted in the yield, and there does not appear to be any generally accepted precise definition of what energy release time scale is considered "prompt." Also a complication arises in determining the yield of underground nuclear explosions due to energy released by interaction of the neutrons from the explosive device with the surrounding ground. Consequently, there might be slight differences in how the United States and the Soviet Union measure yields.

Yields can be estimated not only through seismic means, but also by other methods. The other methods are based on analysis of the nuclear byproducts of the explosion (radiochemical methods) or measurements of the speed of the shockwave generated by the explosion in the surrounding rock (hydrodynamic methods). Neither radiochemical nor hydrodynamic methods are currently used by the United States to measure routinely the yields of Soviet explosions because they require access to the test site during the test, and in the case of radiochemical methods, may require information about the weapon design that could reveal sensitive information concerning the characteristics of the weapon.

MEASURING THE SIZE OF SEISMIC SIGNALS

At present, U.S. estimates of Soviet yields are generally made using seismic waves recorded at teleseismic distances (distances greater than 2,000 km). Seismic magnitudes can be determined from the amplitudes of P waves, Rayleigh waves, and L_g waves.[2] The various magnitudes are averages based on recordings at several stations. The magnitudes are then converted to explosive yields using formulas developed through past experience. The formulas used are based on testing experience at the Nevada test site and at the test site operated in the Sahara by France in the 1960s. The three magnitude measures most often used in yield estimation are: the P-wave magnitude m_b the surface wave magnitude M_s, and the L_g-wave magnitude $m_b(L_g)$.

---

[1] The definition is not precise for two reasons. First, there is some variation in the experimental and theoretical values of the explosive energy released by TNT (although the majority of values lie in the range from 900 to 1,100 calories per gram). Second, the term "kiloton" could refer to a short kiloton ($2x10^6$ pounds), a metric kiloton ($2.205x10^6$ pounds), or a long kiloton ($2.24x10^6$ pounds).

[2] A description of the various types of seismic waves is presented in Chapter 3, The Role of Seismology.

The m_b is computed from measurements of P-wave recordings by the use of the formula

$$m_b = \log (A/T) + B.$$

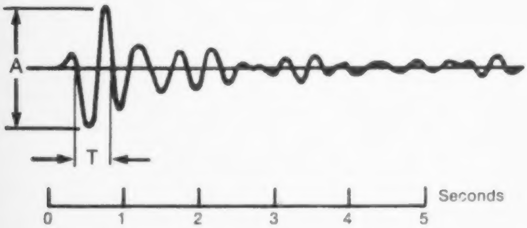
As illustrated in figure 7-1, A is the largest P-wave amplitude in nanometers (0.000000001 meters) measured peak-to-peak from a seismic short-period recording during the first few seconds of the P wave and correcting it for the instrument magnification, T is the duration of one cycle of the wave in seconds near the point on the record where the amplitude was measured (for P waves the period is typically 0.5 to 1.5 seconds), and B is a distance-dependent correction term that compensates for the change of P-wave amplitudes with distance.

The surface wave magnitude is determined by measuring the Rayleigh-wave amplitude near the point where the dominant period of the wave is nearest to 20 seconds on long-period vertical component records. The formula used is

$$M_s = \log (A/T) + D,$$

where A and T are the amplitude and the period measured off long-period vertical component seismic recordings, again in nanometers and seconds, and D is a distance-dependent correction term for Rayleigh waves.

Figure 7-1.—Computation of P-Wave Magnitude



Measurement made on P waves to obtain the magnitude of a seismic event. The peak-to-peak amplitude (A) in the first few seconds of the P wave is corrected for the instrument magnification at the dominant period T.

The magnitude measure derived from measurements of L_g waves is computed from the formula

$$m_b\ (L_g) = 5.0 + \log [A(10km)/110],$$

where A(10 km) is the maximum sustained amplitude of L_g on short-period vertical records in nanometers extrapolated backwards to a distance 10 km from the source by dividing by the geometrical spreading factor of $d^{-5/6}$, where d is the source-to-receiver distance, and by the estimated attenuation along the path. The empirical $m_b(L_g)$ v. log Yield (Y) relationship also includes a small second-order term, giving

$$m_b(L_g) = 3.943 + 1.124 \log Y - 0.0829 (\log Y)^2$$

for explosions in water saturated rocks such as those at the Nevada Test Site.

The m_b magnitude is routinely used at teleseismic distances for yield estimation because P waves are detectable at large distances, even for small seismic events. This measure can almost always be obtained for any seismic event that is detected. The measurement of M_s requires a larger event, because Rayleigh waves are small for nuclear explosions. For explosions below 50 kt, M_s may be missed altogether at teleseismic distances. The L_g amplitude is similarly weak for small explosions. **Consequently, it may be important for seismic stations to be close to the explosion if surface waves and L_g waves are to be used for yield estimation of explosions less than 50 kt.** This is one of the reasons why seismic stations within the territories of the treaty participants are desirable. The distance correction factors can be quite variable regionally, and hence, some of the magnitude-yield relationships will need to be adjusted for different regions.

In addition to the conventional surface wave magnitude M_s, a new measure of source strength for surface waves is coming into wide use. Called *seismic moment* (M_o), it is an estimate of the strength of a compressional (explosion-like) force at the explosion site. Seismic moment gives a direct description of the force system, acting in the Earth, that would make seismic waves of the size and shape actually recorded. The advantage of using seismic moment is that the computation can correct for the estimated effects of contamination of the seismic signals due to earthquake-like motion triggered by the explosion. This is useful because nuclear explosions often release stress that has been built up in the area of the explosion by geological processes. The release of built-up stress by the explosion creates a surface wave pattern similar to that observed for earthquakes, which is seen superimposed on the signals of the explosion. Characteristics of an earthquake, such as Love waves and reversed polarities in the Rayleigh waves, are often observed from a nuclear explosion, indicating release of pre-existing stress. If not removed, this release of natural stress by the explosion, called *tectonic release*, can distort yield estimates obtained from conventional M_s.

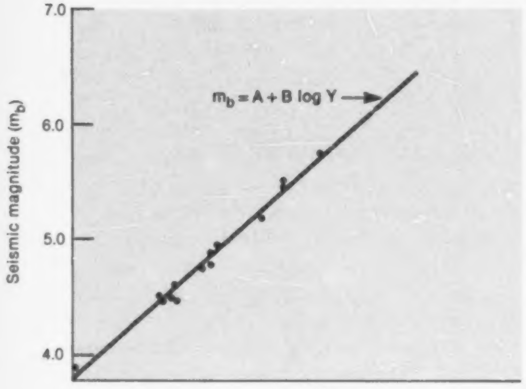
DETERMINING EXPLOSIVE YIELD FROM SEISMIC MAGNITUDE

Once the seismic magnitude measurements have been made, the next step is to relate the magnitude measurements to the yield of the explosion. Because we know the actual yields only of U.S. tests and some French nuclear explosions (the Soviets have announced yields only for a few of their tests), our knowledge is based on data other than Soviet data. The actual data used to derive this relationship are shown in figure 7-2. The relationship between the yield of a nuclear explosion and the measured seismic magnitude can be described using an equation of the general form

$$M = A + B \log Y + \text{Bias Correction}$$

where M is a magnitude measure (or moment) from surface waves, body waves, or L_g waves, A and B are constants that depend on which magnitude measure is used, and Y is the yield in kilotons. The specific constants used by the United States for these calculations are classified. The "Bias Correction" term is an adjustment made to correct for the differences in how efficiently seismic waves travel from the various test sites. This correction is particularly important for m_b, because short-period body waves are strongly affected by the physical state (especially temperature) of the medium through which they travel.

Figure 7-2.—Explosions in Granite



Data for explosions in granite from which the magnitude v. yield equation is derived.

SOURCE: Modified from Air Force Technical Application Center.

The empirical magnitude-yield relationships for m_b that are used to estimate yields at inaccessible test sites in the U.S.S.R. and elsewhere have been revised several times during the last two decades. These revisions were improvements in yield formulas and computational procedures to correct for such problems as difficulties in merging magnitude sets from different station configurations and instruments, clipping (limiting the maximum recordable amplitudes) of large signals by the recording systems, and not correctly accounting for differences in the geology at different test sites. The early magnitude-yield formulas were based on the simplifying assumption that all nuclear explosions in granite at any site follow a simple linear relationship between m_b and log(yield). After the factors listed above were properly considered, however, it became obvious that bias corrections for each test site were needed.

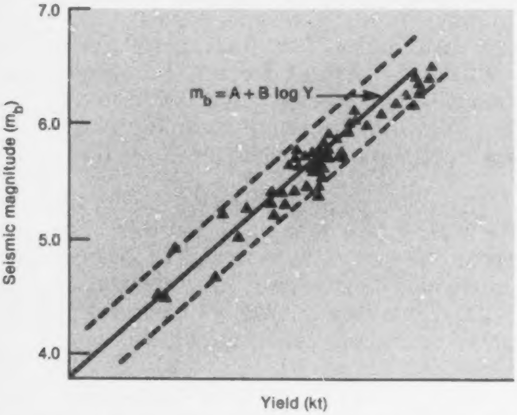
SOURCES OF UNCERTAINTY

Under the ideal conditions of a perfectly uniform and symmetrical Earth, it would be possible to estimate yields of nuclear explosions at any site from measurements at a single seismic station. In practice, however, seismic magnitudes and magnitude-yield plots show scatter. Using data from the International Seismological Centre[3] as an example, individual m_b measurements typically have a standard deviation of 0.3 to 0.4 magnitude units before station corrections are applied. When station corrections are applied, the standard deviation is reduced to 0.1 to 0.15 units. Figure 7-3 illustrates typical scatter in a magnitude-yield plot.

One reason for this variation is the small-scale geologic contrasts in the Earth that cause focusing and scattering of seismic waves. Focusing effects near the recording seismometers can create differences in estimated magnitudes even when the stations are closely spaced. Focusing effects near the explosion can cause broad regional variations of seismic amplitudes so that seismic observatories over whole continents may observe higher or lower average amplitudes than the global average. Fortunately, the uncertainty introduced by focusing effects can be reduced by averaging measurements from numerous stations if the stations are well distributed around the test sites in both distance and direction.

In addition to the scatter due to focusing, geological structures under individual stations may amplify seismic waves. Such effects may

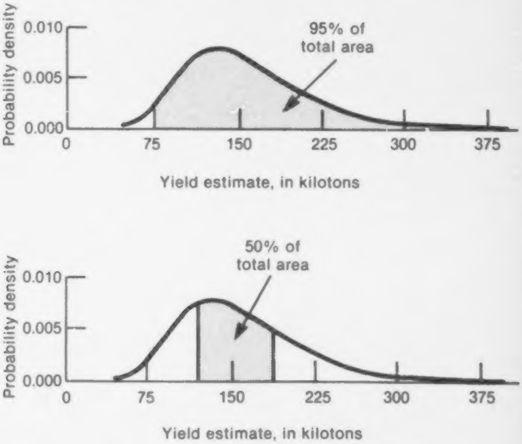
Figure 7-3.—Yield Data From the Nevada Test Site



M_b versus yield for explosions at the Nevada Test Site. The scatter is characteristic of yield measurements when only P-wave magnitudes are used.

SOURCE: Modified from Air Force Technical Applications Center.

Figure 7-4.—Yield Estimate Distribution



Probability of yield estimates for a 150 kt explosion measured with a factor-of-2 uncertainty.

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[3] The International Seismological Centre is an organization based in England that gathers data for the research community from thousands of seismic stations operated all over the globe.

be corrected for by applying statistically derived station corrections that compensate for any such local effects.

After averaging many measurements and applying appropriate corrections, estimates of the yield of a nuclear explosion are expected to be distributed about the "true" value in the manner indicated in figure 7-4. The horizontal axis in this figure is the yield estimate while the vertical axis is the probability that the estimate is correct. The area under the curve between 2 yield values represents the probability that the actual yield is in this interval (the percentage chance is 100 times the probability and the total area under the curve is 1, giving a 100 percent chance that some value of magnitude will be measured). This figure shows that it is most likely that the central yield value (150 kt in this case) will be close to the actual value and that outcomes become increasingly less likely the larger the difference between the estimated value and the central value (see chapter 2 for a more detailed discussion of uncertainty and what it represents). The yield distribution is asymmetric due to the normal distribution of m_b and the logarithmic relationship between the yield of the explosion and the measured seismic magnitude. Figure 7-3 is a typical empirical magnitude-yield curve obtained from actual data at the Nevada test site that shows the measurements do not follow a single line but scatter around it because of measurement errors and variations in rocks surrounding the explosions.

Some of the uncertainty described above is due to variations in how well explosions are coupled to the surrounding rock. Also, explosion depth can influence the amplitudes of the seismic waves emitted, as can variations in the physical properties of the Earth. For inaccessible test sites, these effects result in increased uncertainty in estimating yields. However, if data were exchanged and calibration shots performed, corrections could be made that would greatly reduce the uncertainty. Nevertheless, there will always be some uncertainty in estimates of the yields of Soviet explosions, as in estimates of any physical quantity. This is not unique to seismology. Some uncertainty will exist no matter what type of measurement system is used. Such uncertainty should not necessarily be considered to represent opportunities for cheating. Chapter 2 discusses the meaning of the various uncertainties and their implications for cheating.

BIAS CORRECTION FOR SOVIET NUCLEAR EXPLOSIONS

In estimating the yields of Soviet explosions, a major concern is how well the magnitude-yield formula for U.S. tests can be applied to Soviet test sites. Geophysical research has shown that seismic P waves traveling through the Earth's mantle under the main U.S. test site in Nevada (and many other areas of the world as well) are severely attenuated when compared to most other continental areas, especially those with no history of recent plate tectonic movements. If not corrected for, this attenuation will cause a sizable systematic error in estimates of the yield of Soviet explosions.

The apparent reason for this attenuation is the high temperature in the upper mantle under Nevada and many other tectonically active regions. Regions of high temperatures change the elastic and absorptive properties of the rocks, causing a large loss in the amplitudes of seismic waves traveling through them. Similar phenomena are thought to occur under the French test sites in Algeria and the Pacific, though not under either the Soviet test sites in Kazakh and Novaya Zemlya or the U.S. test sites in Mississippi and Amchitka. If the P-wave magnitudes observed from U.S. tests in Nevada are used as a basis for estimating yields, most Soviet explosions which have been exploded in areas where the upper mantle is cool and there is little attenuation of P waves will appear considerably larger than they actually are.

The evidence for such attenuation effects comes from many studies, including:

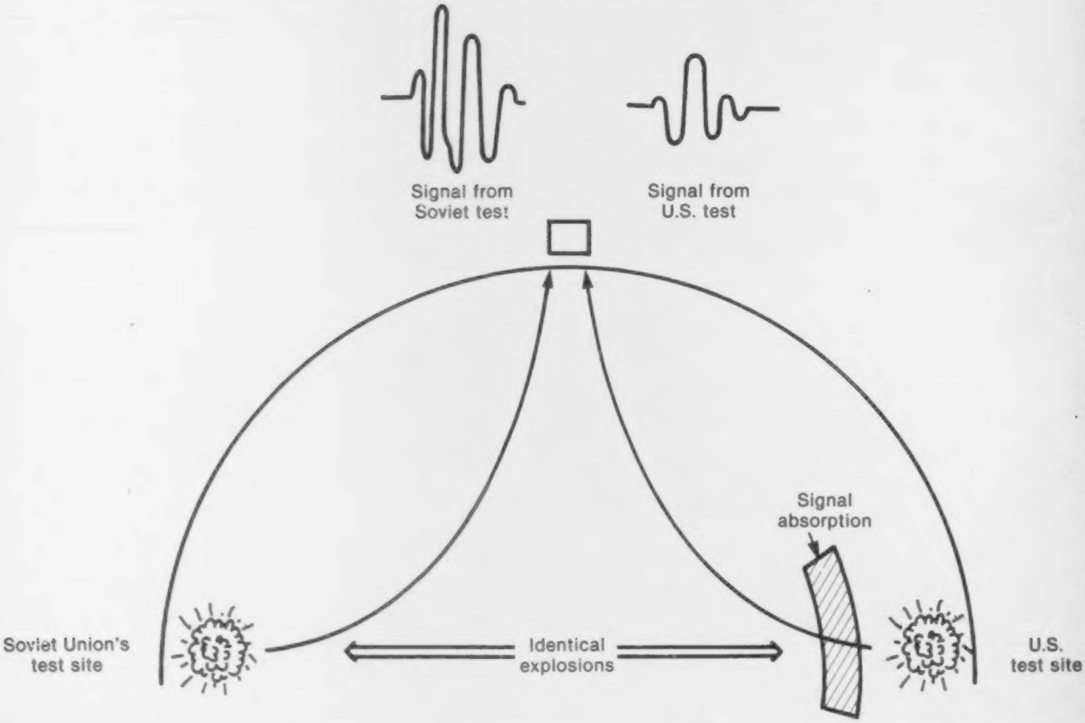
- comparisons of P-wave amplitudes observed at the Nevada test site with observations made at other sites in areas underlain by colder mantle;
- studies of short period S-wave amplitudes, which are very sensitive measures of mantle temperature variations;
- studies of the frequency content of both P and S waves, i.e., the relative loss of high frequency energy in waves traveling through the upper mantle in both directions under Nevada; and
- studies of P- and S-wave velocities, which are also influenced by temperature.

In addition, there is a large amount of independent geophysical evidence supporting the notion of anomalously high temperatures under most of the western United States. This evidence includes:

- measurements of anomalously high heat flow,
- measurements of electrical conductivity, and
- the low velocity P waves (P_n) and the absence of S waves (S_n) that propagate just under the Earth's crust.

These "symptoms" of high attenuation have been observed in many other areas of the world and are recognized as such by most geophysicists. The sketch in figure 7-5 illustrates how

Figure 7-5.—Schematic Illustration of Attenuation-Related Magnitude Bias



Seismic body waves crossing parts of the upper mantle with high temperatures become anonomously reduced in amplitude. Seismic signals from the Soviet Union's test site appear much larger than signals from an identical explosion conducted at the U.S. test site.

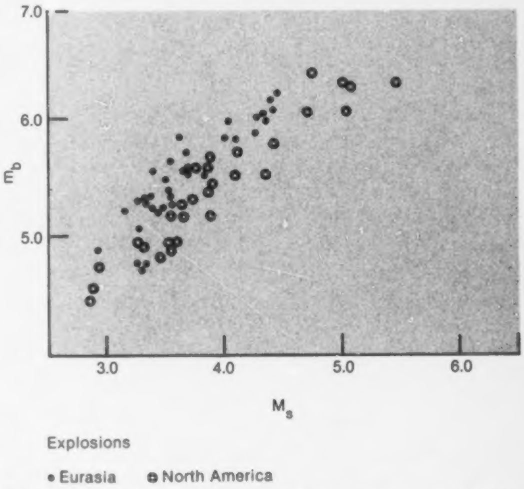
SOURCE: Modified from Defense Advanced Research Projects Agency.

this attenuation is created in the Earth and affects estimates of the size of the wave source. Seismic body waves crossing the hatched high attenuation zones in the upper mantle are reduced in amplitude and high frequency components of wave motion relative to waves that bypass such zones.

Magnitudes derived from Rayleigh waves and L_g waves are less influenced by temperature variations in the mantle because they travel along the surface and largely bypass the high attenuation zones in the upper mantle. A plot of P-wave magnitudes (m_b) against surface wave magnitudes (M_s) should, therefore, show the attenuation of P waves relative to surface waves. By plotting the M_s - m_b ratio of explosions for different test areas, the attenuation in different regions can be compared. Figure 7-6 shows the results of an early study that compared the M_s - m_b for explosions in Eurasia with the M_s - m_b for explosions in North America. It can be seen that the two groups are offset, with explosions of the same M_s value having lower m_b values in North America than in Eurasia. Results like this led to early speculation about the existence of high attenuation zones in the upper mantle.

In general, if the P-wave magnitudes are plotted against the Rayleigh or L_g magnitudes for the Nevada and Soviet test sites, the 2 sets of data are offset by about 0.3 to 0.4 magnitude units (or an amplitude factor of about 2 for P waves).[4] The most likely explanation for this offset is the reduction of P-wave magnitudes due to attenuation at the Nevada test site. Such data constitute additional support for the idea of an attenuation bias for P waves. Offsets can also be brought about by other factors such as contamination of the M_s measurement by tectonic release. However, such contamination can be detected by the strong Love waves the release generates, and reduced by using seismic moment instead of surface wave magnitude (M_s) for yield estimation.

Figure 7-6.—Comparisons of Explosions in Eurasia With Explosions in North America



Explosions with the same M_s value have lower m_b values in North American than in Eurasia. This led to early speculation about the existence of high attentuation zones in the upper mantle.

SOURCE: Modified from P.D. Marshall and P.W. Basham, *Geophysical Journal of the Royal Astronomical Society*, 1972, vol. 28, pp. 431-458.

Various government-supported scientific panels of seismologists, after considering the totality of the geophysical evidence, have repeatedly recommended during the last decade that U.S. yield estimates of Soviet explosions be reduced by subtracting a larger "Bias Correction" term from the magnitudes to account for the attenuation effect on m_b. As a result, the bias correction has been increased on several occasions over the last decade as new scientific evidence indicated that such changes are appropriate.

The size of the bias correction was determined simply by averaging the correction inferred from a number of independent or semi-independent estimates of the attenuation effect made by different researchers. Most evidence for an attenuation "bias" has been indirect thus far, although the evidence from global seismic studies and seismological experience gives strong support to the idea. More direct measurements of this bias may soon become available. The United States and Soviet Union have recently agreed on experiments to calibrate seismic yield estimation methods through measurements at each others test sites. Explosions will be measured with seismic methods and the yields confirmed independently by hydrodynamic methods. In addition, several seismic stations have been set up recently in the Soviet Union near the Kazakh test site by a group of U.S. scientists supported through the Natural Resources Defense Council. Data from these stations will help improve estimates of the bias correction and assess the efficiency of seismic wave propagation at high frequencies to regional distances.

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[4] See for example P. D. Marshall and P. W. Basham, "Discrimination Between Earthquakes and Underground Explosions Employing an Improved M_s Scale," *Geophysical Journal of the Royal Astronomical Society*, vol. 28, pp. 431-458, 1972, and Otto W. Nuttli, "L_g Magnitudes of Selected East Kazakhstan Underground Explosions," *Bulletin of the Seismological Society of America*, vol. 76, No. 5, pp. 1241-1252, October 1986.

The bias correction is currently used as a simple, yield-independent adjustment to the intercept, A, in the m_b-log Y curve. The value currently used by the U.S. Government is intended to be the most appropriate value for yields near the 150 kt threshold of the 1974 Threshold Test Ban Treaty. A different bias may be appropriate for yields that are either much larger or much smaller.

REDUCING UNCERTAINTIES

The estimated yield of an underground of nuclear explosion, like any quantity derived from measurements, has some error associated with it. The error comes from a variety of sources. Some of the error is considered to be *random* in that it varies unpredictably from one measurement to another. Other errors are not random but are *systematic*. Systematic errors are those that always act in the same way, for example, the bias between test sites. If systematic errors are understood, corrections can be made to reduce or eliminate the error.

The distinction between random and systematic errors, however, has no clear boundary. If everything about the Earth and seismic waves were known, almost all errors in seismology would be systematic. In general, random errors usually turn out to be systematic errors once the reason for the error is understood. However, if the systematic errors are not understood, or if there are lots of systematic errors all operating in different ways, then the systematic errors are often approximated as random error. In such cases, random uncertainties are inflated to encompass the unexplained systematic uncertainties.[5]

Random Uncertainty

Different methods of yield estimation have different accuracies and uncertainties. At the Nevada test site, the most precise method uses P-wave magnitudes (m_b). Less precise methods use L_g waves ($m_b(L_g)$), surface waves (M_s), and seismic moment (M_o). At the Nevada test site, yields estimated from m_b alone have a random uncertainty factor of 1.45 at the 95 percent confidence level, whereas those from $m_b(L_g)$ have an uncertainty factor of 1.74, and those from M_o have an uncertainty factor of 2.13.

Recently, the Defense Advanced Research Projects Agency (DARPA) has been able to reduce the random uncertainty in seismic yield estimates at the Nevada test site by combining measurements made by the three different methods. Scientists have shown, using data from U.S. explosions at the Nevada test site, that the random errors of the three types of magnitude measures for a given event can be considered statistically independent. Consequently, an improvement in the accuracy of yield estimates can be achieved by combining several methods to produce a "unified" magnitude measure. By forming a weighted average of the three magnitudes, a "unified seismic magnitude" with an uncertainty factor of 1.33 (figure 7-7) has been derived. Most seismologists believe that if this method were now

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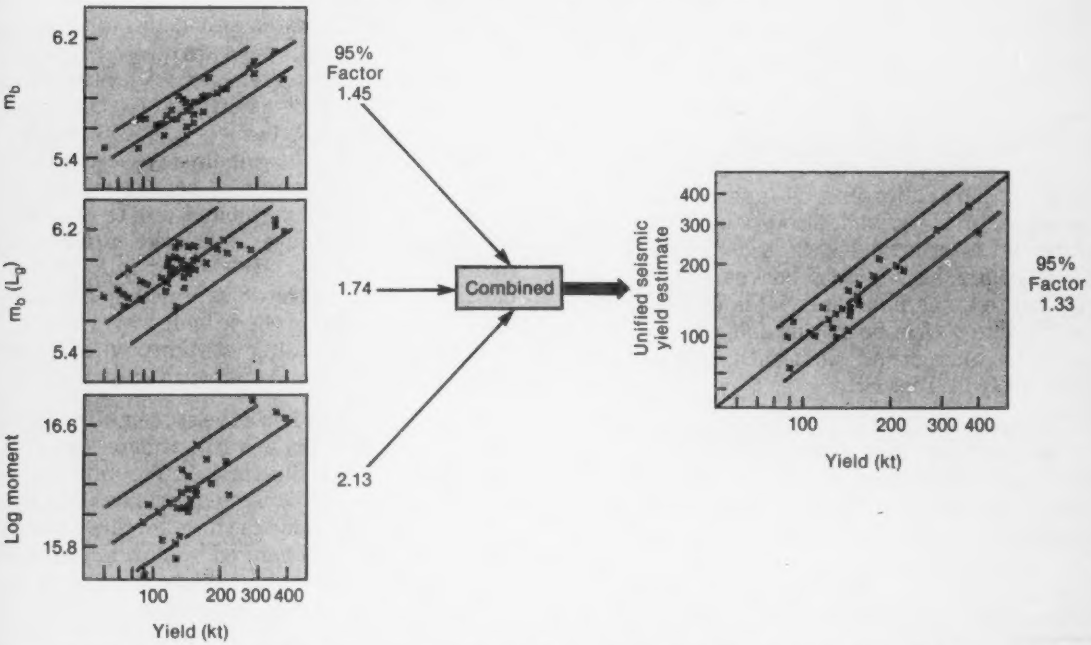
[5] As discussed in Chapter 2, random errors do not provide opportunities for cheating. However, if systematic errors are found to be 1) of sufficient size, 2) usable for an advantage by one side, and 3) unrecognized as being systematic by the other side, then such errors can be exploited under some situations. A treaty should, therefore, contain provisions to reduce the uncertainty of yield estimates and counter evasion opportunities.

Figure 7-7.—Uncertainty in Yield Estimates



Uncertainty in yield estimates can be greatly reduced through the use of a unified seismic yield estimate. On the left are three plots of m_b, $m_b(L_g)$, and M_0 versus yield at the Nevada Test Site. On the right is a similar plot of the unified seismic yield estimate versus the actual yields. The 95 percent uncertainty factors are shown to the right of each plot.

SOURCE: Modified from Defense Advanced Research Projects Agency.

applied to estimating yields at the Soviet test site in Eastern Kazakh, the uncertainty would be reduced to a factor of 1.6 - 1.5 for explosions around 150 kilotons.[6] What limits the uncertainty from being reduced to the level of the Nevada test site (a factor of 1.3) is the systematic uncertainty or bias correction. As we will see later, however, this systematic uncertainty can be reduced through calibration shots.

The expected precisions given above are only for explosions where all waves are used for the estimation. For smaller explosions, the regional Rayleigh and L_g waves are not always strong enough to travel the long distances required to reach seismic stations outside the Soviet Union. Consequently, for monitoring low-yield explosions, stations within the Soviet Union may be necessary to obtain the improved accuracy of the "unified seismic yield" estimation method. The relationship between magnitude and yield for the stations within the Soviet Union will also have to be established.

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[6] Consider, as an example, the situation where there are 3 statistically independent methods of calculating the yield of an explosion, all of which (for the sake of this example) have a factor of 2 uncertainty in a log normal distribution:

# of Methods	Resulting Uncertainty
1	2.0
2	1.6
3	1.5

By combining methods, the resulting uncertainty can be reduced. This methodology, however, can only reduce the random uncertainty. Systematic uncertainty such as differences between the test sites will remain and limit the extent to which the uncertainty can be reduced unless calibration is performed.

As noted above, the formulas derived from the Nevada test site data that describe the relationships between yield and $m_b(L_g)$ and moment M_0 are not directly applicable to the Soviet test site in Kazakh without some as yet unknown adjustments. The values of these adjustments can be determined if stations are placed within the Soviet Union and the Soviet test sites are calibrated. Test site calibrations suitable for lower yields could only take place after an internal network is installed. If the $m_b(L_g)$ and M_0 v. yield curves are suitably calibrated, the absolute yields of explosions at Kazakh should be measurable with the "unified seismic method" just as accurately as at the Nevada Test Site.

The above analysis applies only to explosions at known test sites observed by a large set of well-distributed seismic stations for which the appropriate station corrections and bias correction have been determined. The accuracy with which the yields of "off-site" nuclear tests could be estimated would be less than that stated above. Therefore, to maintain high accuracy in yield estimation, nuclear testing should be prohibited outside specified, calibrated test sites.

Most yield estimation research has concentrated on yields around 150 kt, so the accuracy that could be achieved by seismic methods at lower yields is not yet well known. In any future low threshold test ban treaty, it might be expected that the initial uncertainties in yield estimation for explosions below 10 kt would be large. These uncertainties would then be reduced as more data were gathered, as our knowledge of wave propagation properties for various paths in the monitored regions was refined, and as calibration information was obtained.

Systematic Uncertainty

The yield estimation precisions described above for teleseismic data are limited because of systematic uncertainties. As discussed above, the systematic uncertainty can be reduced by calibrating the test site. Calibrating a test site involves exploding devices whose yields are either known or accurately determined by independent means, and then measuring the magnitudes at a large number of monitoring stations. By doing so, the yields of other events can be determined by comparing the amplitudes of the seismic waves at common seismic recording stations with those originating from the events with known yields.

This approach reduces the systematic uncertainties caused by having to estimate the varying properties of the rocks surrounding the explosion and any focusing effects near the explosion sites. As long as these factors remain approximately unchanged within a geologically uniform area, the calibration improves the estimation of yields.

The sizes and numbers of geophysically distinct subdivisions in any test site depend on the geological structures of the area. A specific calibration may be valid only for a limited area around the shot if, at larger distances, the rock properties and focusing effects change. The distances over which the relevant conditions change vary, depending on the local geology. Testing areas that are large or contain varying geology would obviously need more calibration shots than areas that are geologically uniform. If calibration were performed at the Soviet test site, the expected seismic yield estimation capability would be comparable to the existing seismic capability at the Nevada Test Site.

YIELD ESTIMATION CAPABILITIES

In considering the capability of all methods of yield estimation, it must be kept in mind that it is never possible to determine a yield without some uncertainty. The standard against which yield estimation methods are measured is radiochemical methods. Radiochemical methods of yield estimation have an uncertainty of about 10 percent (a factor of 1.1). Also, experimental devices often detonate with yields that are slightly different from what was predicted.

This uncertainty in predicted yield was recognized during the negotiations of the Threshold Test Ban Treaty and provisions were established for unintended breaches (see ch. 2).

The yields of Soviet underground explosions can be seismically estimated with a much better capability than the factor-of-2 uncertainty that is commonly reported.[7] New seismic methods have greatly improved yield estimation capabilities. Further improvements would occur if the test sites were calibrated and, for small tests, if stations were present within the Soviet Union during the calibration. The capabilities depending on these variables can be summarized as follows:

- *Without Calibration*: For large explosions (above 50 kilotons) seismic yield estimation could be improved with the additional use of the other methods including: surface waves, L_g waves, and seismic moment. Through such a combined method, it is estimated that without calibration Soviet yields can be seismically measured with present resources to a factor of 1.6 to 1.5 uncertainty.
- *With Calibration*: Further reductions in the uncertainty of yield estimates can be accomplished if the Soviet test site were calibrated. At a defined, well-calibrated Soviet test site, it is estimated that yields could be seismically measured with the same factor of 1.3 uncertainty that is found for seismic estimates at the Nevada Test Site. In fact, Soviet seismologists have told U.S. seismologists that they are able to estimate yields seismically at their own test site with only a factor of 1.2 uncertainty.
- *Small Explosions*: For small explosions (below 50 kt), the regional seismic waves may not always be strong enough to travel long distances to seismic stations outside the Soviet Union. Consequently, seismic stations within the Soviet Union may be necessary (in addition to calibration) to obtain the 1.3 factor of uncertainty from combined seismic methods for explosion with yields below 50 kt. At yields below 10 kt small variations of the physical environment may produce greater uncertainty. Therefore, at yields below 10 kt, the uncertainty may be inherently greater.

A 1.3 factor of uncertainty (for yields above 50 kt) is the claimed capability of the hydrodynamic yield estimation method using CORRTEX data[8] that has been proposed as an alternative means for improving yield estimation. Consequently, hydrodynamic yield estimation will not provide a significantly superior yield estimation capability over what could be obtained through well-calibrated seismic means (also a 1.3 factor of uncertainty). Hydrodynamic yield estimation is, however, one of the methods that could be used to provide independent estimates of the yields of calibration shots to improve seismic methods. Once a test site was calibrated using hydrodynamic methods, there would be no need to continue the use of those intrusive methods.

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[7] See, for example, *Verifying Nuclear Testing Limitations: Possible U.S.-Soviet Cooperation* (Washington, DC: U.S. Department of State, Bureau of Public Affairs, Special Report No. 152, Aug. 14, 1986)

[8] See appendix, *Hydrodynamic Methods of Yield Estimation.*

SOVIET TEST PRACTICES AND TEST BAN COMPLIANCE

Specific concern over compliance with test ban treaties has been heightened with findings by the Reagan Administration that:

> Soviet nuclear testing activities for a number of tests constitute a likely violation of the legal obligations under the Threshold Test Ban Treaty.[9]

Such findings are presumably based on net assessments of all sources of data. In measuring yields near the 150 kt limit of the Threshold Test Ban Treaty, however, seismic evidence is considered the most reliable basis for estimating the yields of Soviet underground nuclear explosions.[10] It is, therefore, the seismic evidence that has received particular attention.

Concern about whether the Soviet Union is actually restricting its testing to a maximum yield of 150 kt is motivated by two arguments:

1. The m_b of several Soviet tests at their Shagan River (E. Kazakhstan) test site are significantly larger than the m_b for U.S. tests with yields of 150 kt.
2. The pattern of Soviet testing indicates that the yields of Soviet tests increased after the first 2 years of the treaty.

The validity of the first argument is dependent on how the Soviet yields are calculated. Because of the uncertainty in measuring the yields of Soviet tests using only m_b and because of differences in opinion as to what the correct bias value for Soviet tests should be, there is disagreement as to whether the m_b values of the largest Soviet tests do, in fact, represent violations of the 150 kt limit of the Threshold Test Ban Treaty. For example, when calculations such as those in table 7-1 are made using both m_b and M_s measurements and a bias correction of 0.35, they indicate that the few remaining yields estimated as above 150 kt are well within the expected random scatter, and do not support claims of a violation.

The second argument is dependent on assumptions about probable Soviet behavior. Two years after the signing of the Threshold

Box 7-A.—Calculations of the Six Largest East Kazakhstan Explosions. By Sykes et al., Based on Unclassified Data

6 Largest East Kazakhstan Explosions 1976-1986		
Date	Yield from m_b only	Yield averaged from m_b & M_s
23 June 79	152	149
14 Sept 80	150	150*
27 Dec 81	176	161
4 July 82	158	158*
14 July 84	140	140*
27 Oct 84	140	140*
	Average: 152.7 (± 13.4 kt)	Average: 149.7 (± 8.8 kt)

(*based on m_b only; no M_s determined)

All estimated yields are well within the uncertainty expected for observance of the 150 kt threshold limit.

SOURCE: Calculations of the six largest East Kazakhstan explosions made by Sykes et al., based on unclassified data. Body wave measurements from International Seismological Centre Bulletins and United States Geological Survey Reports. Station corrections determined to be 0.02 to 0.04 from mean. Surface wave calculations made by Sykes et al. Calibration corrected for bias using a value of 0.35 to make body wave data consistent with surface wave data.

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[9] "The President's Unclassified Report on Soviet Noncompliance with Arms Control Agreements," transmitted to the Congress Mar. 10, 1987.

[10] Conclusion of the Defense Intelligence Agency Review Panel as stated in a letter from Roger E. Batzel, Director of Lawrence Livermore National Laboratory to Senator Claiborne Pell on Feb. 13, 1987.

Test Ban Treaty, the size of the largest Soviet explosions at their eastern Kazakh test site increased markedly (see figure 7-8).[11] This increase has been interpreted by some to infer that the Soviets have been violating the 150 kt threshold limit in the later tests. The argument assumes that the Soviets were testing up to the limit for the first 2 years and, therefore, by inference, have been testing above the limit in violation of the treaty ever since 1978. Alternate interpretations for this apparent yield increase have been offered. It has been pointed out that a similar pattern of testing occurred at Kazakh for the 2 years prior to the treaty. It has also been speculated that this increase in yields may reflect a Soviet decision to move their high yield testing from the Novaya Zemlya test site to the Kazah test site.[12] As a non-technical consideration, it can be argued that if the Soviets had tested above the limit of the Threshold Test Ban Treaty at the Kazakh test site, they would never have offered to allow the United States to calibrate their test site using CORRTEX and Soviet test explosions. The calibration will reduce the uncertainty of yield estimates, a reduction that applies to past as well as future explosions and hence can provide more accurate evidence concerning past compliance.

Because of the statistical nature of all yield estimates, the question of compliance can be addressed best not by looking at individual tests but rather by examining the entire pattern of Soviet testing. It is particularly useful to compare the testing programs of the United States and the Soviet Union. It can be seen from figure 7-9 that if a bias value lower than 0.35 is used, there appears to have been about 10 (out of over 200) Soviet tests since the signing of the Threshold Test Ban Treaty in 1974 with yield central values above the 150 kt threshold limit. When the same method of yield

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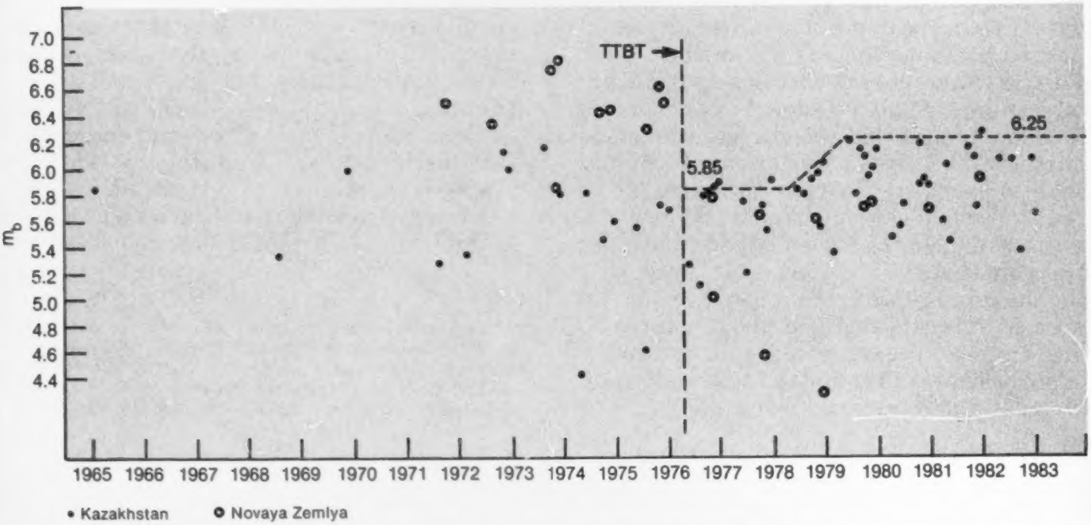
[11] There was also speculation that this increase was coincident with a change in the U.S. official method of yield estimation. For example, Jack Anderson, "Can't Tell If Russia Cheats On Test Ban," *The Washington Post*, Aug. 10, 1982, p. C15.

[12] See for example, "Nuclear Test Yields" (Letter to the Editor), J.F.Evernden and L.R.Sykes, *Science*, vol. 223, Feb. 17, 1984, p. 642.

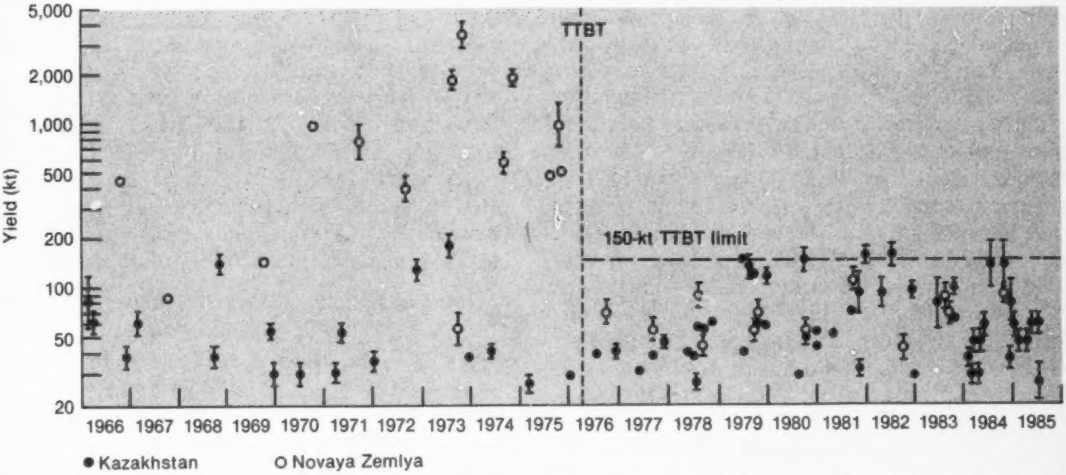
Figure 7-8.—m_b Versus Time for Large Soviet Explosions



The m_b versus time for all large Novaya Zemlya and Kazakhstan explosions. It can be seen that a large increase of the maximum yield for explosions at the Eastern Kzazkh test site occurred about 2 years after the Threshold Test Ban Treaty was signed.

SOURCE: T.C. Bache, S.R. Bratt, and L.B. Bache, "P Wave Attenuation m_b Bias, and The Threshold Test Ban Treaty," SAIC-86-1647, submitted to AFGL, March 1986, p. 5.

Figure 7-9.—U.S.S.R. Nuclear Tests 1966-86 According to Sykes and Davis



These yields were calculated by combining P-wave and surface-wave magnitudes and using a bias correction of 0.35. Bars denote the estimated standard deviations of the estimates. The few tests that do appear to have exceeded 150 kt are well within the expected scatter. If a lower bias correction is applied and only P-wave determinations are used, then slightly higher yield estimates will result and additional central values will be greater than 150 kt.

SOURCE: Modified from L.R. Sykes and D.M. Davis, *Scientific America*, vol. 256, No. 1, January 1987, pp. 29-37.

estimation is applied to U.S. tests, approximately the same number of U.S. tests also appear to be above the 150 kt threshold limit. This, however, does not mean that one or the other or both countries have cheated; nor does it *de facto* mean that seismology is an inadequate method of yield estimation. It is inherent in *any* method of measurement that if both countries are testing up to the yield limit, the estimated yields of some tests will have central values above the yield limit. Because of the uncertainty of measurements using *any* method, it is expected that about half the Soviet tests at 150 kt would be measured as slightly above 150 kt and the other half would be measured as slightly below 150 kt.

All of the estimates of Soviet tests are within the 90 percent confidence level that one would expect if the yields were 150 kt or less. Extensive statistical studies have examined the distribution of estimated yields of explosions at Soviet test sites. These studies have concluded that the Soviets are observing a yield limit. The best estimate of that yield limit is that it is consistent with compliance with the 150 kt limit of the Threshold Test Ban Treaty.[13]

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[13] Such statistical studies have been carried out extensively by Lawrence Livermore National Laboratory. The conclusion of these studies was reported in open testimony before the Senate Armed Services Committee on Feb. 26, 1987 by Dr. Milo Nordyke, Leader of the Treaty Verification Program.

Appendix

Appendix

Hydrodynamic Methods of Yield Estimation

Hydrodynamic methods could be used to complement seismic methods of yield estimation

Introduction

The yield of an underground nuclear explosion may be estimated using so-called hydrodynamic methods. These methods make use of the fact that larger explosions create shock waves that expand faster than the shock waves created by smaller explosions. Three steps are involved in making a yield estimate. First, the properties of the geologic media at the test site that may affect the expansion of the shock wave are determined. Second, the expansion of the shock wave caused by the explosion of interest is measured during the hydrodynamic phase, when the ambient medium behaves like a fluid. Finally, the yield of the explosion is estimated by fitting a model of the motion of the shock front to measurements of the motion.

Although the algorithms used by different individuals or groups can (and usually do) differ in detail, most of the algorithms currently in use are of four basic types: insensitive interval scaling, similar explosion scaling, semi-analytical modeling, and numerical modeling. Before considering these algorithms and their application to test ban verification, it will be helpful to have in mind how the shock wave produced by an underground nuclear explosion evolves during the hydrodynamic phase and how this evolution is affected by the properties of the ambient medium.

Shock Wave Evolution

The hydrodynamic evolution of the shock wave produced by a large, spherically symmetric explosion underground may be usefully divided into three different intervals. These are listed in table A-1, along with the times after detonation at which they begin for 1 and 150 kiloton (kt) explosions in granite. The characteristics of these intervals follow.

Self-Similar Strong-Shock Interval

At the very earliest times, the energy of the explosion is carried outward by the expanding weapon debris and by radiation. Soon, however, a shock wave forms and begins to move outward. At this time the speed of the shock wave is much greater than the speed of sound in the undisturbed ambient medium, the pressure behind the shock wave is predominantly thermal pressure, and the ratio of the density behind the shock wave to the density in front is close to its limiting value. This is the *strong shock* interval.[1]

Table A-1.—Characteristic Times in the Evolution of a Shock Wave Caused by an Underground Nuclear Explosion[a]

Event in the evolution of the shock wave	Time (μs) for a 1 kt explosion	Time (μs) for a 150 kt explosion
Beginning of the Self-Similar Strong Shock Interval[b]	–	~10
Beginning of the Transition Interval[c]	~20	~80
Beginning of the Plastic Wave Interval[d]	~2,000	~10,000

[a] For an idealized spherically-symmetric explosion in granite.

[b] Here the shock wave is assumed to become self-similar when it reaches a radius of 1 m (see text). No time is given for a 1 kt explosion because the shock wave caused by such an explosion typically weakens before it has time to become self-similar.

[c] Defined as the time when the density just behind the shock front falls to 80 percent of its maximum limiting value.

[d] Defined as the time when the speed of the shock wave falls to 120 percent of the plastic wave speed. In reality, granite undergoes a phase transition slightly before the shock speed reaches this value, a complication that has been neglected in this illustration.

SOURCE: F. K. Lamb, "Hydrodynamic Methods of Yield Estimation," Report for the U.S. Congress, Office of Technology Assessment, Feb. 15, 1988.

If the shock wave envelops a mass of material much greater than the mass of the nuclear charge and casing while it is still strong, and if energy transport by radiation can be neglected, the shock wave will become *self-similar*, expanding in a particularly simple way that depends only weakly on the properties of the medium.[2] The time at which the motion becomes self-similar depends in part on the design of the nuclear charge and diagnostic equipment and on the size of the emplacement hole. As the shock wave expands, it weakens and slows, the density behind the shock front drops, and the wave enters a transition interval in which the motion is no longer self-similar. No time is given in table A-1 for the beginning of the self-similar strong-shock interval for a 1 kt explosion because the shock wave produced by such an explosion typically weakens before it has time to become self-similar.

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[1] See Ya. B. Zel'dovich and Yu. P. Riazer, *Physics of Shock Waves and High-Temperature Phenomena* (New York, NY: Academic Press, 1967 [English Translation]), ch. XI. As the strength of a shock wave is increased, the ratio of the material density immediately behind it to the material density immediately in front of it generally increases, until a value of the ratio is reached beyond which an increase in the strength of the shock wave produces little or no further increase in the density of the post-shock material. This density ratio is referred to as the limiting density ratio. In typical rocks, pressures behind the shock front of about 10-100 Mbar are needed to produce a density ratio close to the limiting value.

[2] Ibid., ch. I and XII.

Transition Interval

As the shock wave weakens and slows, it enters a broad transition interval in which the thermal pressure is not much greater than the cold pressure of the medium. The motion of the shock wave changes only gradually and so the time at which the transition interval is said to begin is purely conventional. In this report the shock wave is considered to have entered the transition interval when the density just behind the shock front has fallen to 80 percent of its maximum limiting value. The speed of the shock front is only a few times greater than the relevant sound speed—the speed of the so-called plastic wave—in the medium over much of the transition interval and hence the motion of the shock wave in this interval is more sensitive to the properties of the medium than it is in the strong shock interval.[3]

Plastic-Wave Interval

In the absence of phase transitions and other complications,[4] the shock wave weakens and slows still further, entering an interval in which the pressure behind the shock front is predominantly the cold pressure of the compressed ambient medium and the shock speed is close to the plastic wave speed in the medium. Again, the motion of the shock wave changes only gradually and so the time at which the plastic-wave interval is said to begin is purely conventional. In this report the shock wave is considered to have entered the plastic-wave interval when its speed is less than 120 percent of the plastic wave speed in the medium. In practice, phase transitions and other effects complicate the evolution of the shock wave in this interval for rocks of interest.

Theoretical models and experimental data show that the evolution of the shock wave in all three intervals depends on such properties of the rock as its chemical composition, bulk density, plastic wave speed, and degree of liquid saturation. These properties vary considerably from one rock to another. As a result, the shock wave generally develops differently in different rocks. For example, the characteristic radius at which the shock wave produced by a 150 kt explosion changes from a strong, self-similar wave to a plastic wave[5] varies from about 30 meters in wet tuff to over 60 meters in dry alluvium.

Measuring the Position of the Shock Front

Several techniques have been used to measure the position of the shock front as a function of time. During the 1960s and early 1970s, extensive measurements were made using the so-called SLIFER technique.[6] In the mid-1970s an improved technique, called CORRTEX, was developed.[7] This is the technique the Reagan administration has proposed as a new technique to monitor the Threshold Test Ban Treaty (TTBT).[8]

In the CORRTEX technique, an electrical sensing cable is lowered into a vertical hole to a depth greater than the depth at which the nuclear explosion will take place, typically hundreds of meters for explosives with yields near 150 kt. The hole may be the one in which the nuclear explosive is placed (the *emplacement hole*) or one or more other holes (so-called *satellite holes*) that have been drilled specifically for this purpose. The latter geometry is shown in figure A-1. If satellite holes are used, they must be drilled at the proper distance(s) from the emplacement hole, typically about ten meters for yields near 150 kt. Then, if the sensing cable is strong enough that it is not crushed by other dis-

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[3] Ibid., pp. 741-744.

[4] Ibid., ch. XII.

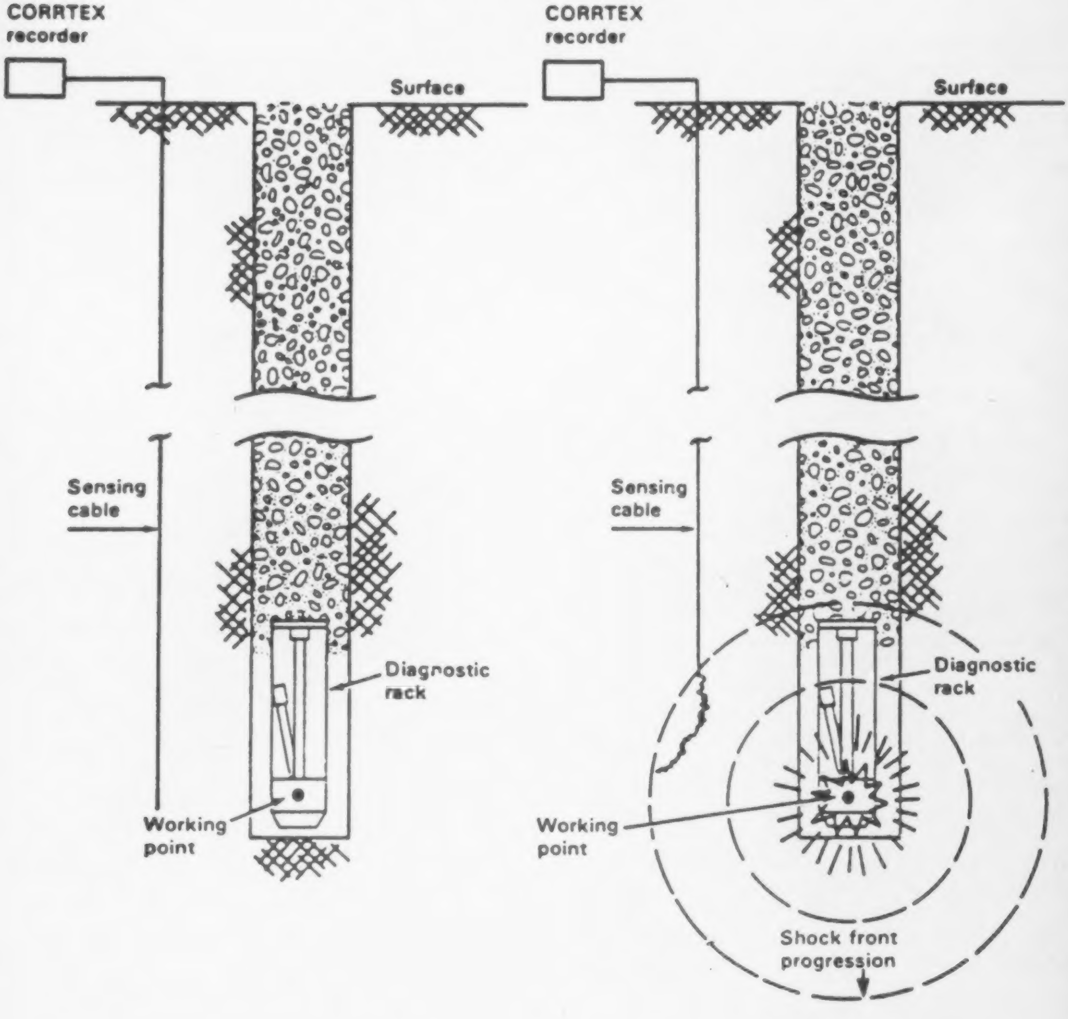
[5] See F. K. Lamb, ACDIS WP-2-87-2 (University of Illinois Program in Arms Control, Disarmament, and International Security, Urbana, IL, 1987).

[6] M. Heusinkveld and F. Holzer, *Review of Scientific Instruments*, 35, 1105 (1964). SLIFER is an acronym for "Shorted Location Indication by Frequency of Electrical Resonance."

[7] C.F. Virchow, G.E. Conrad, D.M. Holt, et.al., *Review of Scientific Instruments*, 51, 642 (1980) and Los Alamos National Laboratory public information sheet on CORRTEX (April 1986). CORRTEX is an acronym for "Continuous Reflectometry for Radius v. Time Experiments."

[8] U.S. Department of State, Bureau of Public Affairs, "U.S. Policy Regarding Limitations on Nuclear Testing,"Special Report No. 150, August 1986; and U.S. Department of State, Bureau of Public Affairs, "Verifying Nuclear Testing Limitations: Possible U.S.-Soviet Cooperation," Special Report No. 152, Aug. 14, 1986.

Figure A-1.—Use of the CORRTEX Technique


CORRTEX recorder
Surface
Sensing cable
Diagnostic rack
Working point
CORRTEX recorder
Surface
Sensing cable
Diagnostic rack
Working point
Shock front progression

Typical cable emplacement in satellite hole

Moving shock wave from nuclear detonation crushes and shortens cable

SOURCE: U.S. Department of State, Bureau of Public Affairs, "U.S. Policy Regarding Limitations on Nuclear Testing," Special Report No. 150, August 1986.

turbances but weak enough that it is crushed by the pressure peak at the shock front, it will be electrically shorted close to the point where the shock front intersects the cable (see figure A-1). As the shock front expands with time, the changing distance from the surface to the shallowest point at which the shock wave intersects the sensing cable is measured at preset time intervals by electrical equipment attached to the cable and located above ground. The CORRTEX technique is much less affected by disturbing early signals from the explosion than were earlier techniques.

The time at which the explosion begins is taken to be the time at which the first signal, produced by the electromagnetic pulse (EMP) from the explosion, arrives at the CORRTEX recorder. If the explosion is spherically symmetric, the length of the unshorted cable decreases rapidly and smoothly with time as the shock front expands away from the center of the explosion and the radius of the shock front at a given time can be calculated using simple geometrical equations. If the explosion is not spherically symmetric, due to the shape of the canister, the design of the nuclear charge, or inhomogeneities in the ambient medium, the interpretation of CORRTEX data is more complicated and could be ambiguous or misleading under the conditions encountered in treaty verification. Problems of this kind can be prevented by cooperative agreements, as discussed below.

An error of 1 meter in the measured distance of the crushing point from the center of the explosion will cause an error of about 50 kt in the yield estimate, for yields near 150 kt. Thus, an accurate survey of the satellite hole is required in order to make an accurate yield estimate. Surveys are currently made with special laser or gyroscopic equipment. In some yield estimation algorithms, the lateral displacement from the center of the explosion can be treated as one of the unknowns in estimating the yield.

Yield Estimation Algorithms

Hydrodynamic methods of yield estimation are evolving as research aimed at gaining a better understanding of underground explosions and improving yield estimation methods continues. At present, four basic types of algorithms are commonly in use. In order to simplify their description, the explosion will be assumed to be spherically symmetric (the complications that can arise if it is not will be addressed later).

Insensitive Interval Scaling

Once measurements of the radius of the shock front as a function of time are in hand, an estimate of the yield of the explosion can be made by comparing the measurements with a model of the motion of the shock front away from the center of the explosion. The simplest algorithm currently in use is *insensitive interval scaling*. This is the algorithm that the Reagan administration has proposed to use in analyzing CORRTEX data as an additional new method of monitoring compliance with the 150 kt limit of the TTBT.

Insensitive interval scaling is based on the assumption that the radius of the shock wave for an explosion of given yield is independent of the medium during a certain interval in time and radius called here the *insensitive interval*. Indeed, studies indicate that for the collection of rocks within U.S. test experience (mostly silicates), rock properties are correlated in such a way that there is a time during the transition interval when the radius of the shock front produced by an explosion of given yield varies relatively little from one rock to another.[9]

In using insensitive interval scaling, the shock wave sensing cable must be placed close enough to the center of the explosion that it samples the insensitive interval. Yield estimates are then derived by fitting a simple empirical formula, called the Los Alamos Formula, to the shock radius versus time data in this interval.[10] The Los Alamos Formula is a power law that approximates the actual radius versus time curve during the insensitive interval. This is illustrated by figure A-2, which compares the Formula with a model of the evolution of the shock wave produced in granite by a spherically-symmetric point explosion with a yield of 62 kt.

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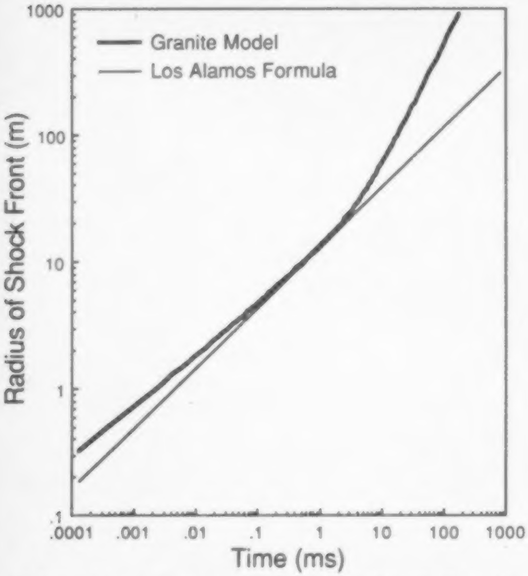
[9] The rocks for which the United States had good data or models are the dry alluvium, partially saturated tuff, saturated tuff, granite, basalt, and rhyolite at the test sites used, almost all of which are at the Nevada Test Site. At present, the reason for the correlation of rock properties that gives rise to the insensitive interval is not well understood from a fundamental physical point of view. Moreover, it is known that the radius of the shock wave in this interval is very different for other very different kinds of rocks. Thus, the existence of an insensitive interval must be established by test experience or modeling, and is only assured for certain geologic media.

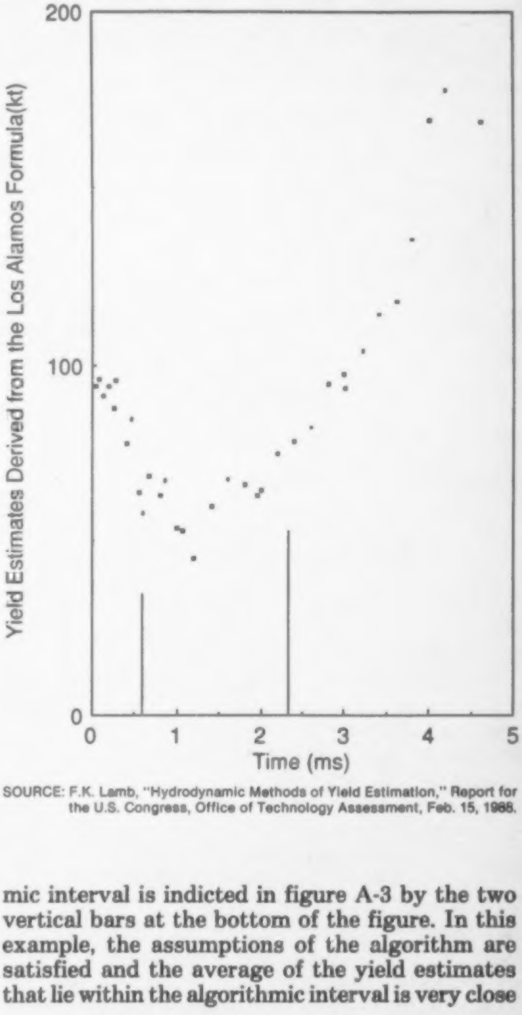
[10] The Los Alamos Formula for the shock radius in meters is $R(t) = \alpha \cdot W^{1/3}(t/W^{1/3})^{\beta}$, where W is the yield of the explosion in kilotons, t is the elapsed time since the beginning of the explosion in milliseconds, and α and β are constants. Different values of α and β have been used by different individuals and groups and have changed with time. The values of α and β used here are 6.29 and 0.475 (see M. Heusinkveld, *Journal of Geophysical Research*, 87, 1891, 1982).

Figure A-2.—Comparison of the Los Alamos Formula With a Semi-Analytical Model of the Shock Wave in Granite Caused by a Spherically-Symmetric Point Explosion With a Yield of 62 Kilotons



SOURCE: F.K. Lamb, "Hydrodynamic Methods of Yield Estimation," Report for the U.S. Congress, Office of Technology Assessment, Feb. 15, 1988.

Figure A-3.—Application of the Los Alamos Formula to an Explosion in Granite



SOURCE: F.K. Lamb, "Hydrodynamic Methods of Yield Estimation," Report for the U.S. Congress, Office of Technology Assessment, Feb. 15, 1988.

In practice, the Los Alamos Formula is usually first fit to a broad interval of radius versus time data that is thought to include the insensitive interval. The result is a sequence of yield estimates. Due to the departure of the Formula from the actual radius versus time curve at both early and late times, the sequence of yield estimates typically forms a U-shaped curve. This is illustrated in figure A-3, which shows the sequence of yield estimates obtained by applying the Formula to the relatively high-quality SLIFER data from the Piledriver explosion in granite. If the assumptions on which the algorithm is based are satisfied, the yield estimates near the bottom of the curve approximate the actual yield of the explosion, In the usual form of the algorithm, only the radius versus time data that fall within a certain predetermined interval chosen on the basis of previous experience (the so-called *algorithmic interval*) are actually used to make the final yield estimate. The length of the algorithmic interval and the time at which it occurs are both proportional to $W^{1/3}$, where W is the yield of the explosion (see table A-2). The algorithmic interval is indicted in figure A-3 by the two vertical bars at the bottom of the figure. In this example, the assumptions of the algorithm are satisfied and the average of the yield estimates that lie within the algorithmic interval is very close

Table A-2.—Algorithmic Intervals for Various Yields[a]

Time	Time interval (ms)	Radius interval (m)
1	0.1-0.5	2-4.5
10	0.2-1.1	4.5-10
50	0.4-1.8	8-17
100	0.5-2.7	10-21
150	0.5-2.6	11-24

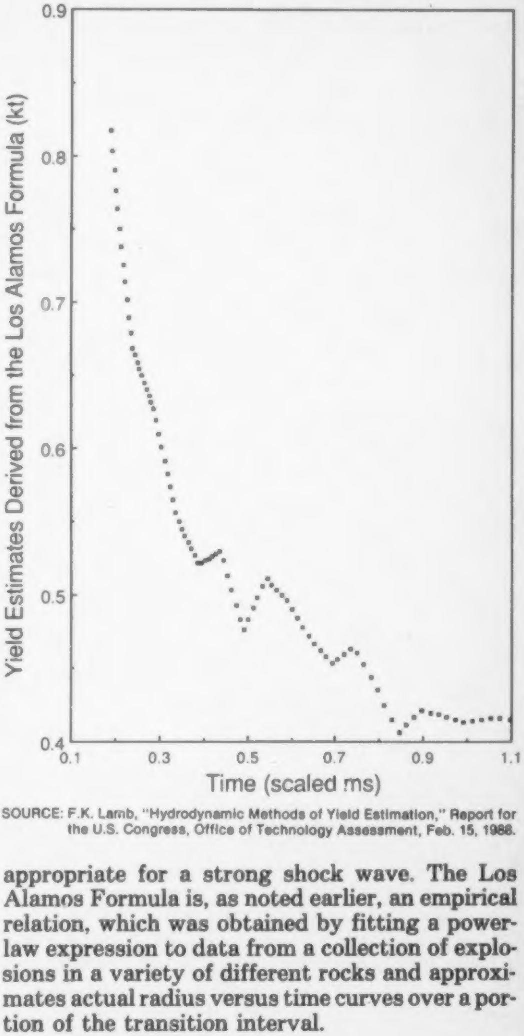
[a] The time intervals used by various individuals and groups varies. Throughout this report the algorithmic interval is taken to be from $0.1W^{1/3}$ milliseconds to $0.5W^{1/3}$ milliseconds after the beginning of the explosion, where W is in kilotons.

SOURCE: F.K. Lamb "Hydrodynamic Methods of Yield Estimation" Report for the U.S. Congress, Office of Technology Assessment, Feb. 15, 1988.

to the announced yield of 62 kt. Studies indicate that yield estimates made using this algorithm have a precision of about a factor of 1.2 at the 95 percent confidence level for spherically-symmetric explosions with yields greater than 50 kt conducted at the Nevada Test Site (NTS). Estimates of the accuracy of the algorithm made by comparing results with the usually more accurate radiochemical method are similar. According to official statements, the insensitive interval algorithm is expected to be accurate to within a factor of 1.3 at Soviet test sites for explosions with yields greater than 50 kt in media within U.S. test experience.[11] Some scientists believe that the uncertainty would be somewhat larger.

The insensitive interval algorithm does not work as well if the assumptions on which it is based are not satisfied. This is illustrated in figure A-4, which shows the yield estimates obtained by fitting the Los Alamos Formula to good-quality SLIFER data from a typical low-yield explosion in alluvium. In this example the radius and time data have been scaled using the actual yield so that the derived yield should be 1 kt. However, the yield estimates given by the Los Alamos Formula are systematically low, ranging from 30 to 82 percent of the actual yield, and do not form a U-shaped curve. The average of the yield estimates that lie within the algorithmic interval is about 60 percent of the actual yield. The overall appearance of the yield versus time curve shows that the assumptions of the algorithm are not satisfied.

Figure A-4.—Application of the Los Alamos Formula to a Low-Yield Explosion in Alluvium



SOURCE: F.K. Lamb, "Hydrodynamic Methods of Yield Estimation," Report for the U.S. Congress, Office of Technology Assessment, Feb. 15, 1988.

A common misconception has been that the algorithmic interval lies within the strong shock region and that the relative insensitivity of yield estimates to the properties of the medium stems from this.[12] As explained earlier, radius versus time data in the algorithmic interval would indeed be relatively independent of the medium if this were so, and would follow a power-law curve similar to the Los Alamos Formula. However, the shock wave is *not* strong during the algorithmic interval, *because* in this interval the shock speed is only a few times the speed of sound and the post-shock pressure is much less than the pressure required to achieve the maximum limiting density. Indeed, the exponent of time usually used in the Los Alamos Formula is significantly greater than the value appropriate for a strong shock wave. The Los Alamos Formula is, as noted earlier, an empirical relation, which was obtained by fitting a power-law expression to data from a collection of explosions in a variety of different rocks and approximates actual radius versus time curves over a portion of the transition interval.

Similar Explosion Scaling

If a given explosion occurs in the same medium as a previous explosion at a different site, and if radius versus time data and the yield are available for the previous explosion, then the yield of the given explosion can be estimated by *similar explosion scaling*. The reason is that for explosions in the same medium, the radius versus time curve depends only on the yield of the explosion, and this dependence is known and is simple.[13] Hence, an estimate of the yield of the given explosion can be made by comparing the two sets of radius versus time data. This algorithm can make use of data outside the insensitive interval and works well if the ambient media at the two explosion sites are sufficiently similar. However, in practice it has sometimes proved difficult to ascertain whether the relevant properties of the media are similar enough to give the desired accuracy. Similar explosion scaling has been proposed as a supplement to insensitive interval scaling for TTBT verification.

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[11] U.S. Department of State, op. cit., footnote 8.

[12] For example, "The accuracy of the method is believed to be relatively, but not wholly, independent of the geologic medium, provided the satellite hole measurements are made in the 'strong shock' region . . ." (Ibid.) This misconception may have arisen from the fact that the interval formerly used to estimate the yields of nuclear explosions in the atmosphere using hydrodynamic methods *is* within the strong shock region.

Semi-Analytical Modeling

Semi-analytical modeling is another approach that is useful for studying the evolution of shock waves in geologic media and for estimating yields. In this approach both the properties of the ambient medium and the motion of the shock front are treated in a simplified way that nevertheless includes the most important effects. The result is a relatively simple, semi-analytical expression for the radius of the shock front as a function of time. If the required properties of the ambient medium are known and inserted in this expression, the yield of an explosion can be estimated by fitting the expression to measurements of the shock wave motion with time.[14] Semi-analytical algorithms can in principle make use of more of the data than can the insensitive interval algorithm and can also be used to estimate the uncertainty in the yield caused by uncertainties in the properties of the ambient medium.

Numerical Modeling

If a treatment that includes the details of the equation of state and other properties of the ambient medium is required, or if the explosion is asymmetric, modeling of the motion of the shock front using numerical hydrocodes may be necessary.[15] In principle, such simulations can provide radius versus time curves that extend over much of the shock wave evolution, making it possible to base yield estimates not only on data from the transition interval but also data from later phases of the shock wave evolution. In practice, the yield estimates obtained using such a procedure are fairly sensitive to the equation of state of the ambient medium, which is known with sufficient accuracy for only a few geologic media. If adequate equation of state data are lacking, numerical modeling may not be warranted.

In summary, the shock wave produced by an underground nuclear explosion propagates differently in different media and different geological structures. As a result, knowledge of the ambient medium and local geological structures is required in order to make accurate yield estimates using hydrodynamic methods. Several different yield-estimation algorithms have been developed. These algorithms, like those based on seismic methods, involve some complexity and require sophistication to understand and apply correctly. Some key terms that have been introduced in this discussion are listed and explained in table A-3.

Application to Monitoring Treaties

Assuring Accuracy

Ambient Medium.—The physical properties and geologic structure of the ambient medium enter directly into yield estimates based on hydrodynamic methods. Incorrect assumptions about the average properties of the ambient medium may bias the yield estimate, decreasing its accuracy, while small-scale variations will cause scatter in the radius versus time data, decreasing the precision of the yield estimate. Thus, it is important to gather information about the types of rock present at the test site and their properties, including their chemical composition, bulk density, and degree of liquid saturation, as well as the speed of sound in the ambient medium and any specific features of the local geologic structure that could affect the yield estimate. Availability of the required data would need to be assured by appropriate cooperative measures.

Some information about the geologic medium at the test site could be obtained by examining the contents of the hole drilled for the CORRTEX sensing cable. Verification could be improved by cooperative arrangements that would also allow observation of the construction of the emplacement hole, removal and examination of rock core or rock frag-

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[13] See H. L. Brode, *Annual Review of Nuclear Science*, 18, 153-202 (1968).

[14] For an early semi-analytical model, see M. Heusinkveld, *Report UCRL-52648* (Lawrence Livermore National Laboratory, Livermore, CA, 1979). For improved semi-analytical models, see F. K. Lamb, *ACDIS WP-87-2-1* (University of Illinois Program in Arms Control, Disarmament, and International Security, Urbana, IL, February 1987); W. C. Moss, *Rep. UCRL-96430 Rev. 1* (Lawrence Livermore National Laboratory, Livermore, CA, July 1987); and R. A. Axford and D. D. Holm, *Proc. NEDC* (Los Alamos, October 1987).

[15] For a discussion of numerical models currently in use see F. K. Lamb, "Monitoring Yields of Underground Nuclear Tests," *Threshold Test Ban Treaty and Peaceful Nuclear Explosions Treaty, Hearings Before the Committee on Foreign Relations, United States Senate* (Washington, DC: U.S. Government Printing Office, 1987), pp. 359-370.

Table A-3.—Glossary of Hydrodynamic Yield Estimation Terms

Term/Explanation

Strong Shock Interval: The interval in radius and time during which the speed of the shock wave is much greater than the speed of sound in the unshocked medium

Transition Interval: The interval in radius and time outside the strong shock interval in which the speed of the shock wave approaches the speed of sound in the unshocked medium

Plastic Wave Interval: The interval in radius and time outside the transition region in which the speed of the weakening shock wave is approximately the plastic wave speed

SLIFER Technique: A technique for measuring the position of the shock wave expanding away from an underground explosion by determining the resonant frequency of an electrical circuit that includes a sensing cable placed in a hole in the ground near the site of the explosion

CORRTEX Technique: A technique for measuring the position of the shock wave expanding away from an underground explosion by determining the round-trip travel time of electrical pulses sent down a sensing cable placed in a hole in the ground near the site of the explosion

Insensitive Interval Scaling: A yield estimation algorithm in which the Los Alamos Formula is fit to measurements of the position of the expanding shock wave as a function of time during the algorithmic interval

Los Alamos Formula: The empirical formula used in the insensitive interval scaling algorithm to make yield estimates by fitting to shock radius versus time data

Algorithmic Interval: The special time interval used in insensitive interval scaling during which the radius of the shock wave is relatively insensitive to the ambient medium; usually assumed to be 0.1-0.5 scaled milliseconds after the beginning of the explosion

Similar Explosion Scaling: A yield estimation algorithm in which data obtained from a previous explosion in the same medium are scaled to fit measurements of the position of the expanding shock produced by the explosion under consideration

SOURCE: F.K. Lamb "Hydrodynamic Methods of Yield Estimation" Report for the U.S. Congress, Office of Technology Assessment, Feb. 15, 1988.

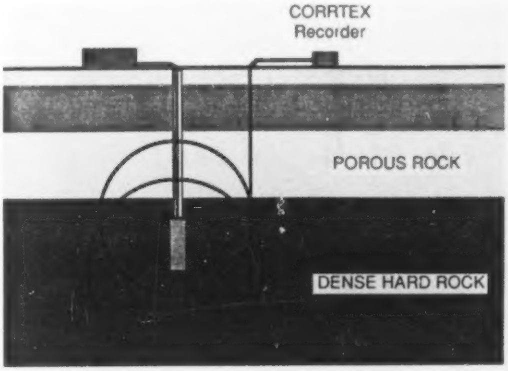
ments from the wall of the emplacement hole, examination of any logs or drill core from existing exploratory holes, removal and examination of rock core or rock fragments from the walls of existing exploratory holes, and if necessary, construction of new exploratory holes.

There is precedent for such cooperative arrangements in the Peaceful Nuclear Explosions Treaty (PNET), which explicitly established the hydrodynamic method as one of the monitoring methods that could be used for large salvos and specified verification measures like these.[16]

Test Geometry.—CORRTEX data must be taken very close to the center of the explosion in order to cover the insensitive interval (see table A-2). As a result, yield estimates can be affected by the arrangement of the nuclear charge and the canister or canisters containing it and the diagnostic equipment.[17] In particular, any properties of the experimental set-up or the surrounding geologic media that cause the shock front to be distorted at the radii of interest could affect the accuracy of the yield estimate. The reason is that a CORRTEX sensing cable measures only the depth of the shallowest point where a pressure wave first crushes it, at a single lateral displacement from the explosion. Thus, unambiguous interpretation of the data may become difficult or impossible if the explosion is not spherically symmetric.

For example, explosions of nuclear charges in tunnels may be accompanied by complicated (and unanticipated) energy flows and complex shock wave patterns. If significant energy reaches the sensing cable ahead of the ground shock and shorts it before the ground shock arrives, the CORRTEX data will describe that flow of energy and not the motion of the ground shock. Alternatively, the motion of the ground shock itself could be sufficiently distorted that interpretation of the shock position data becomes ambiguous or misleading. As another example, a large canister or double explosion could short the CORRTEX cable in such a way that only part of the total yield is sensed over most of the interval sampled by the CORRTEX cable, as shown in figure A-5. The physical size of

Figure A-5.—Effect of Nuclear Test Design on Shock Wave Radius Measurements Using CORRTEX Equipment



SOURCE: F.K. Lamb, "Hydrodynamic Methods of Yield Estimation," Report for the U.S. Congress, Office of Technology Assessment, Feb. 15, 1988.

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[16] *Arms Control and Disarmament Agreements* (U.S. Arms Control and Disarmament Agency, Washington, DC, 1982).

[17] The importance of these disturbing effects is less for high-yield than for low-yield explosions.

canisters and diagnostic lines-of-sight tend to pose more of a problem for nuclear directed-energy weapons than for traditional nuclear weapons.[18]

In using hydrodynamic methods to estimate the yields of one's own tests, the design and placement of the nuclear charge and related equipment are known and can be taken into account. This is not necessarily the case when monitoring the nuclear tests of another party. Cooperative agreements to make possible optimal placement of sensing cables and to exclude nuclear test geometries that would significantly disturb the yield estimate would therefore be required.[19]

Such agreements could, for example, limit the length of the canister containing the nuclear charge and the cross-sectional dimensions of the emplacement hole, and mandate filling of the nuclear charge emplacement hole with certain types of materials. Such agreements could also provide for observation of the emplacement of the nuclear charge and the stemming of the emplacement hole, confirmation of the depth of emplacement, and limitations on the placement of cables or other equipment that might interfere with the CORRTEX measurement. For test geometries that include ancillary shafts, drafts, or other cavities, additional measures, such as placement of several sensing cables around the weapon emplacement point, may be required to assure an accurate yield estimate. For tunnel shots, sensing cables could be placed in the tunnel walls or in a special hole drilled toward the tunnel from above. Again, there is precedent for such cooperative measures in the PNET.[20]

The restrictions on the size of canisters and diagnostic lines-of-sight that would be required even with the sensing cable placed in a satellite hole would cause some interference with the U.S. nuclear testing program at NTS. However, these restrictions have been examined in detail by the U.S. nuclear weapon design laboratories and the Department of Energy, and have been found to be manageable for the weapon tests that are planned for the next several years. In assessing whether hydrodynamic methods should be used beyond this period, the disadvantages of the test restrictions must be weighed against the potential contribution to treaty monitoring made by these methods.

In summary, the accuracy that could be achieved using hydrodynamic methods to estimate the yields of underground nuclear explosions depends on the amount of information that can be gathered about the medium in which the explosion occurs, and the nature and extent of cooperative arrangements that can be negotiated to optimize the placement of sensing cables and to limit disturbing effects.

Hydrodynamic methods for estimating the yields have not yet been studied as thoroughly or as widely as the seismic methods currently in use, although they have been examined more thoroughly than some seismic methods that have been proposed for the future. Tests and simulations to identify troublesome configurations have been carried out, but only a few explosions have been monitored with the CORRTEX sensing cable in a satellite hole.[21] Given the possibility that hydrodynamic yield estimation may have to be used to monitor treaty compliance in an adversarial atmosphere, the possibility of deliberate efforts to introduce error or ambiguity, and the tendency for worst-case interpretations to prevail, additional research to reduce further the chances of confusion, ambiguity, spoofing, or data denial would be very useful.

Minimizing Intrusion

Hydrodynamic yield estimation methods are more intrusive than remote seismic methods for several reasons:

1. Personnel from the monitoring country would be present at the test site of the testing country for perhaps 10 weeks or so before as well as during each test, and would therefore have an opportunity to observe test preparations. The presence of these personnel would pose some operational security problems.[22]
2. The exterior of the canister or canisters containing the nuclear charge and diagnostic equipment must be examined to verify that the restrictions necessary for the yield estimate to be valid are satisfied. For tests of nuclear directed energy weapons, this examination could reveal sensitive design information unless special procedures are followed.[23]

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[18] See Sylvester R. Foley, Jr., Assistant Secretary for Defense Programs, Department of Energy, letter to Edward J. Markey, Congressman from Massachusetts, Mar. 23, 1987.

[19] S. S. Hecker, *Threshold Test Ban Treaty and Peaceful Nuclear Explosions Treaty, Hearings Before the Committee on Foreign Relations, United States Senate* (Washington, DC: U.S. Government Printing Office, 1987), pp. 50-61 and 226-235; M. D. Nordyke, *Ibid.*, 67-71 and 278-285; Foley, ibid

[20] Op. cit., footnote 16.

[21] Op. cit., footnote 8. Approximately 100 tests have been carried out with the CORRTEX cable in the emplacement hole, and SLIFER data from satellite holes are available for several tens of earlier explosions.

[22] R. E. Batzel, *Threshold Test Ban* . . ., op. cit., footnote 19, pp. 48-50 and 210-225, and Foley, op. cit., footnote 18.

[23] Batzel, ibid.

3. Sensing cables and electrical equipment will tend to pick up the electromagnetic pulse (EMP) generated by the explosion. A detailed analysis of the EMP would reveal sensitive information about the design and performance of the nuclear device being tested.

Intrusiveness could be minimized by careful attention to monitoring procedures and equipment. For example, the electrical equipment required can be designed to avoid measuring sensitive information about the nuclear devices being tested. CORRTEX equipment has been designed in this way, and the United States could insist that any Soviet equipment used at NTS be similarly designed. The security problems posed by opportunities to observe test preparations are more severe for nuclear directed energy weapon tests, since they tend to have more and larger complex diagnostic systems and canister arrangements which, if fully revealed to the Soviets, might disclose sensitive information. The United States has determined that the Soviet personnel and activities that would be required at NTS to monitor U.S. tests would be acceptable both from a security standpoint and from the standpoint of their effect on the U.S. test program. Detailed operational plans have been developed to accommodate such visits without adverse impact on operations.[24]

Specific Applications

Threshold Test Ban Treaty.—As noted earlier, hydrodynamic yield estimation has been proposed by the Reagan administration as a new routine measure for monitoring the sizes of nuclear tests, in order to verify compliance with the 150 kt limit of the TTBT. To reduce the cost and intrusiveness of such verification, it could be restricted to tests with expected yields greater than some threshold that is an appreciable fraction of 150 kt. Hydrodynamic measurement of the yields of one or more nuclear explosions at each country's test site or sites has also been suggested as a method of calibrating seismic yield estimation methods.[25]

From the point of view of the United States, possible advantages of being able to use hydrodynamic yield estimation methods at Soviet test sites include the additional information on yields that this would provide, establishment of the principle of on-site inspection at nuclear test sites, and the possibility of collecting data on the ambient media and geologic structures at Soviet test sites. Obviously, the larger the number of explosions and the greater the number of test sites monitored, the more information that would be obtained. Possible disadvantages for the United States include the potential difficulty of negotiating routine use of hydrodynamic methods at Soviet test sites, which could impede progress in limiting nuclear testing, and the operational security problems at NTS caused by the presence of Soviet monitoring personnel there.

Peaceful Nuclear Explosions Treaty.—As it stands, the PNET does not provide for use of hydrodynamic yield estimation except for salvos in which the "planned aggregate yield" is greater than 150 kt.[26] Thus, if the TTBT is modified to allow hydrodynamic yield estimation for all weapon tests with planned yields above a certain value, the purpose of the modification could in principal be circumvented by carrying out weapon tests as "peaceful" nuclear explosions of "planned yield" less than or equal to 150 kt, unless the PNET is also modified to close this loophole.

Low-Threshold Test Ban Treaty.—Underground nuclear explosions as small as 1 kt produce shock waves that evolve in the same way as those produced by explosions of larger yield. However, such explosions can and usually are set off at shallow depths and can be set off in alluvium. As a result, the motion of the ground can be markedly different from that on which standard hydrodynamic yield estimation methods are based, causing a substantial error in the yield estimate (see figure A-4). There can also be significant variations in the motion of the ground shock from explosion to explosion under these conditions.

In addition, serious practical, operational, and engineering problems arise in trying to use hydrodynamic methods to estimate the yield of such a small explosion. For one thing, the sensing cable must be placed very close to the nuclear charge (see table A-3). Drilling a satellite hole within 3 meters of the emplacement hole to the depths of typical nuclear device emplacement, as would be required in order to use hydrodynamic methods to estimate the size of an explosion with a yield near 1 kt, would be challenging, to say the least. The need for such close placement would necessitate further restrictions on the maximum size and orientation of the canister used to contain the nuclear charge and diagnostic instrumentation. Such restrictions might be deemed an unacceptable interference with test programs. However, use of small canisters with numerous diagnostic lines-of-sight to the detonation point could disturb the CORRTEX measurements. Because the shock wave radii to be measured are much smaller at low yields, survey errors become much more important.

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[24] Foley, op. cit., footnote 18.

[25] It has been suggested that the nuclear calibration charges to be detonated at the test sites could be provided by the monitoring country. If they were, a hydrodynamic estimate of the yield might not be needed, since, as explained in ch. 7, the yields of certain types of nuclear charges are accurately reproducible. Knowledge of the surrounding medium and geologic structure would still be needed to provide assurance that the coupling of the explosion to seismic waves was understood. However, some way would have to be found to provide assurance that no sensitive information about the design of the nuclear weapons of either country would be revealed.

[26] *Arms* . . . , op. cit., footnote 16.

Possible solutions to these problems have not yet been carefully and thoroughly studied. Thus, at the present time hydrodynamic yield estimation methods could not be used with confidence to monitor compliance with threshold test bans in which the threshold is less than several tens of kilotons.

Comprehensive Test Ban.—As their name implies, hydrodynamic yield estimation methods have been developed to measure the sizes of underground nuclear explosions. They are a potentially valuable component of a cooperative program to monitor limits on yields, but are neither intended nor able to detect, identify, or measure the yields of unannounced or clandestine nuclear tests. Thus, they are not applicable to monitoring a comprehensive test ban.

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